基于强流重离子加速器的超核谱仪关键技术研究
课题四：超子与超核的产生和极化效应的研究

超子极化理论研究进展汇报

刘天博
山东大学

2026年8月16日

SHANDONG UNIVERSITY

汇报提纲

- ❖ 课题承担项目任务
- ❖ 课题进度安排
- ❖ 研究进展
  - 研究背景与前期探索
  - DIS过程中靶碎裂机制与超子自旋转移压低效应
  - $pp \to pK\Lambda$ 遍举过程超子产生与极化
  - 高能反应产生正反夸克对的量子纠缠
- ❖ 总结

课题承担项目任务

课题承担单位：

香港中文大学（深圳）

山东大学

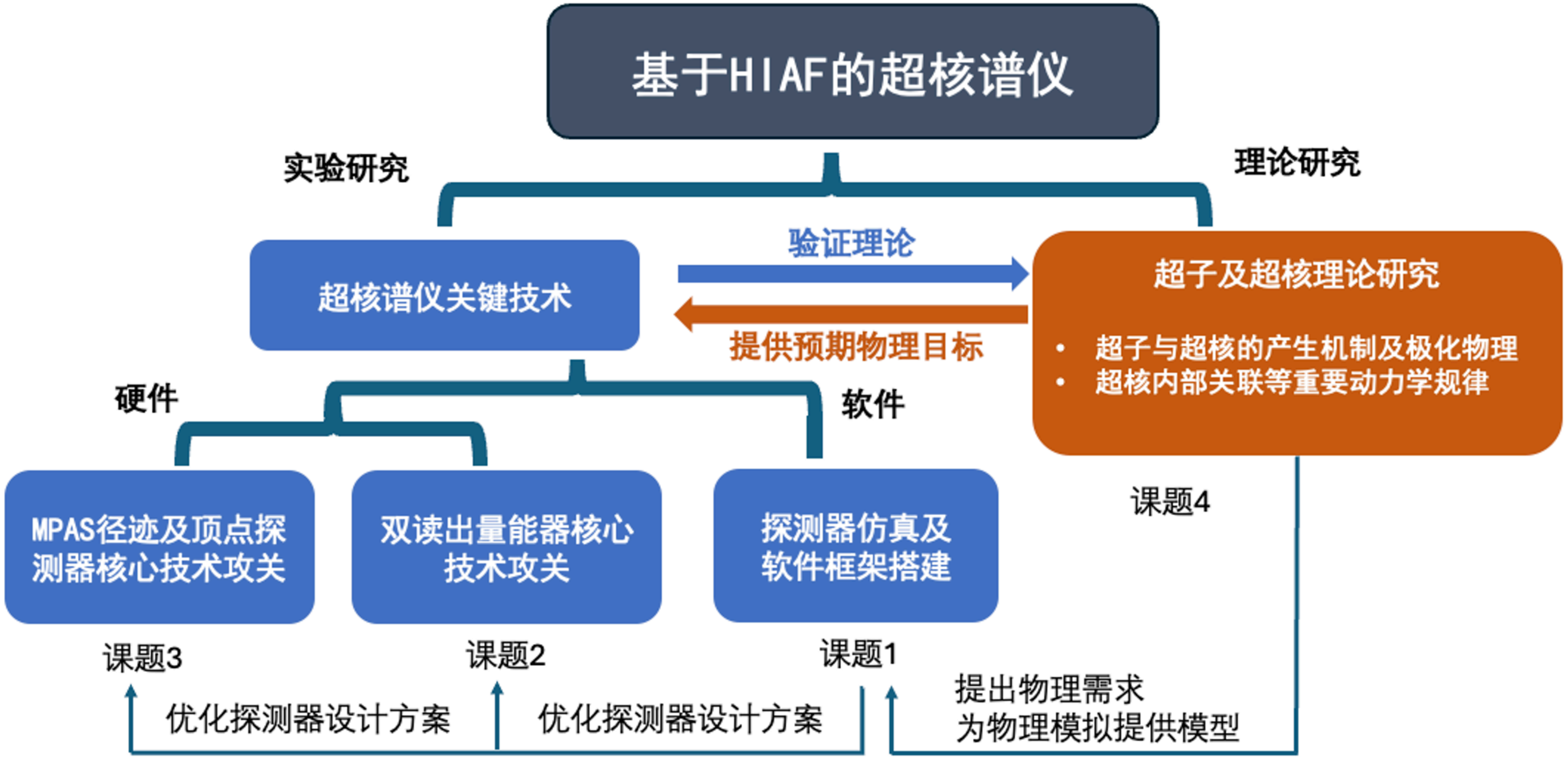
课题负责人：

肖博文

学术骨干：

刘天博、张建辉、

周凯 等



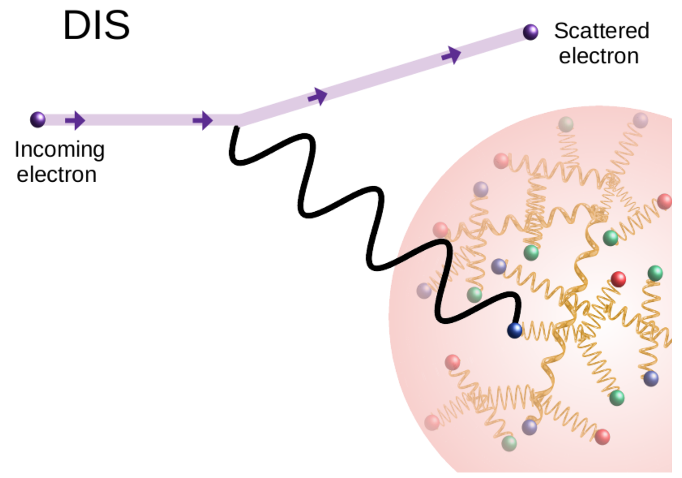
课题进度安排

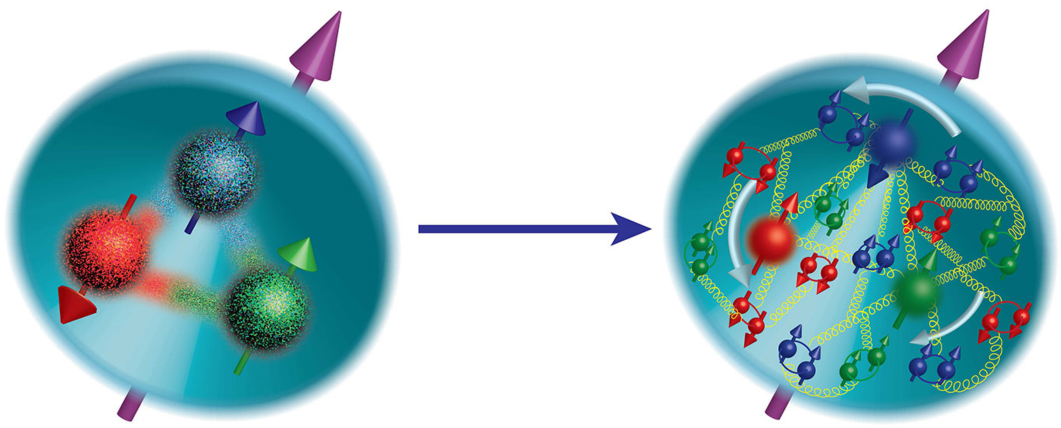
	第一年度	第二年度	第三年度	第四年度	第五年度
聚焦于建立统一的超子极化碎裂函数和中低能区pp和pA过程超子极化反常现象。	核子碰撞中超子极化				
中期目标：系统研究不同产生过程pp、pA、AA中超子极化，构造理论框架并对HIAF能区给出预言。			重离子碰撞中超子极化		
终期目标：建立不同系统中超子极化理论框架；建立超核产生模型及超子对核物质状态方程影响的定量模型。				超子-核子相互作用	

高能反应实验中系列“意外自旋效应”

质子自旋危机

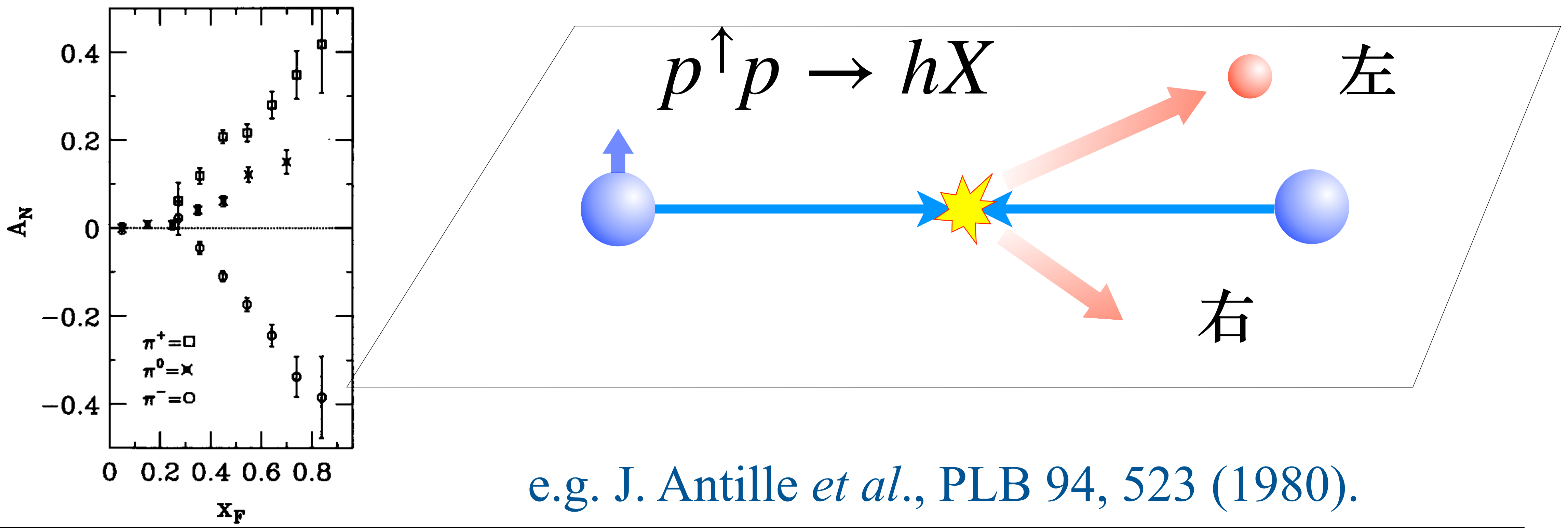
夸克模型:$\Delta\Sigma = 1$，DIS实验:$\Delta\Sigma \sim 0.3$





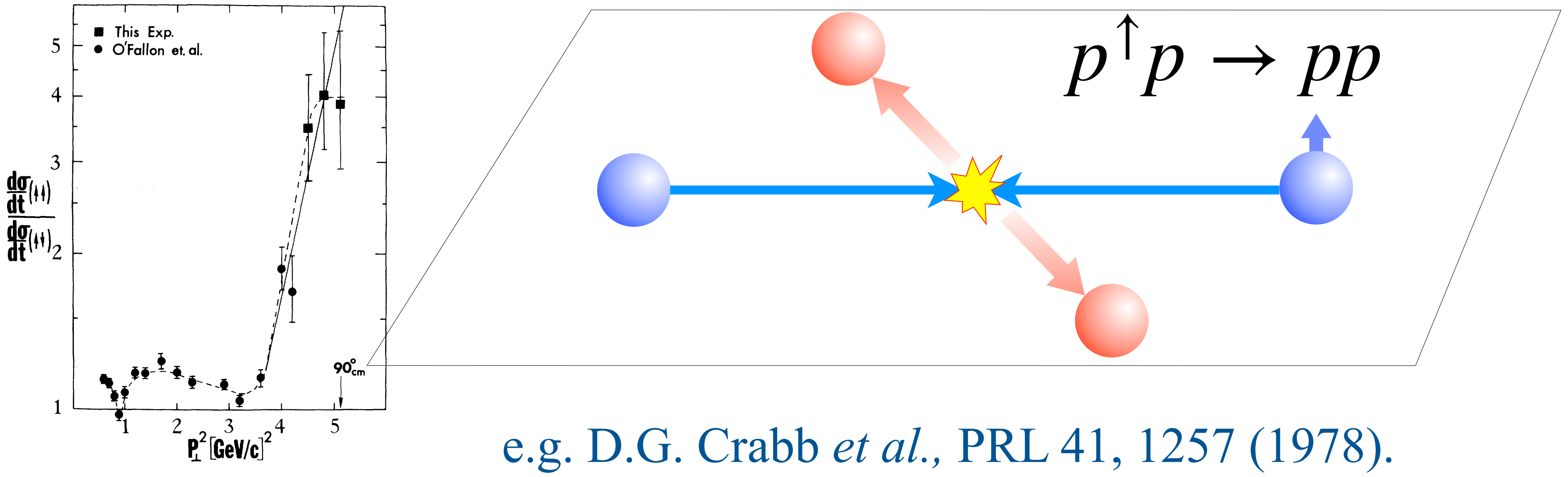
J. Ashman *et al.*, PLB 206, 364 (1988); NP B328, 1 (1989).

单自旋左右不对称



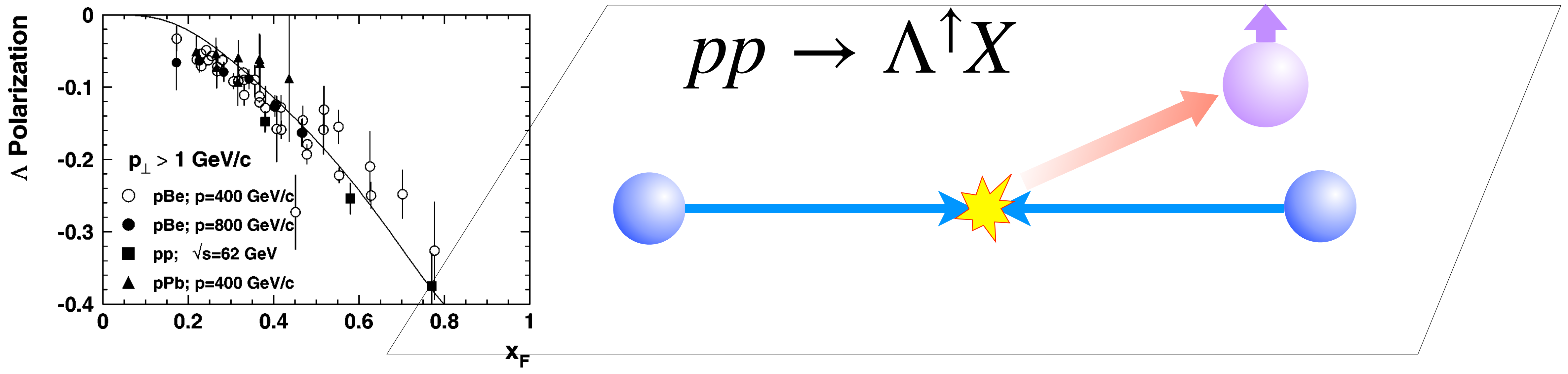
e.g. J. Antille *et al.*, PLB 94, 523 (1980).

极化质子弹性散射



e.g. D.G. Crabb *et al.*, PRL 41, 1257 (1978).

超子横向极化



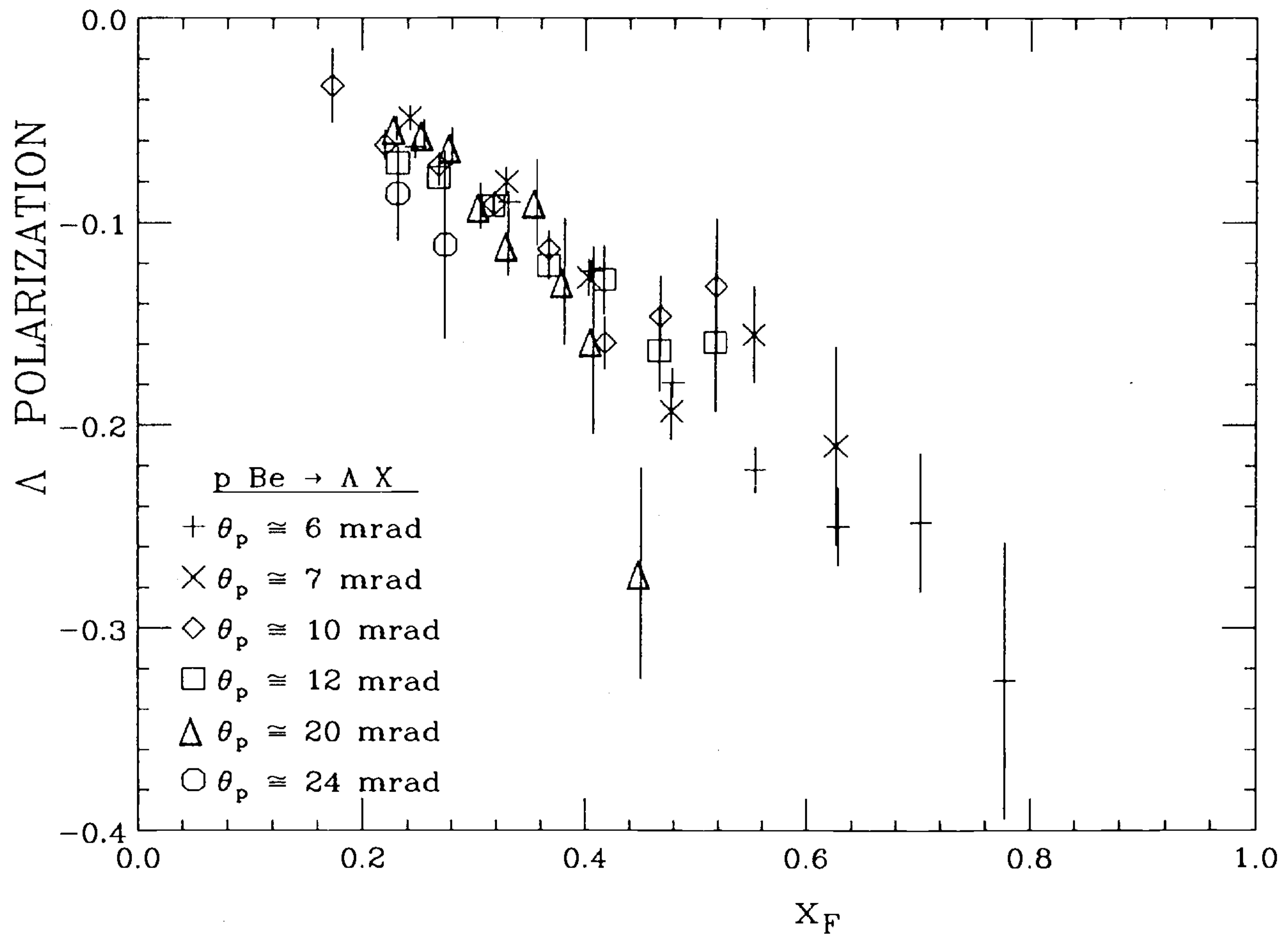
e.g. G. Bunce *et al.*, PRL 36, 1113 (1976).

实验与理论严重冲突 ⇒ 自旋成为QCD研究的一个突破口

非极化强子碰撞产生超子横向极化现象

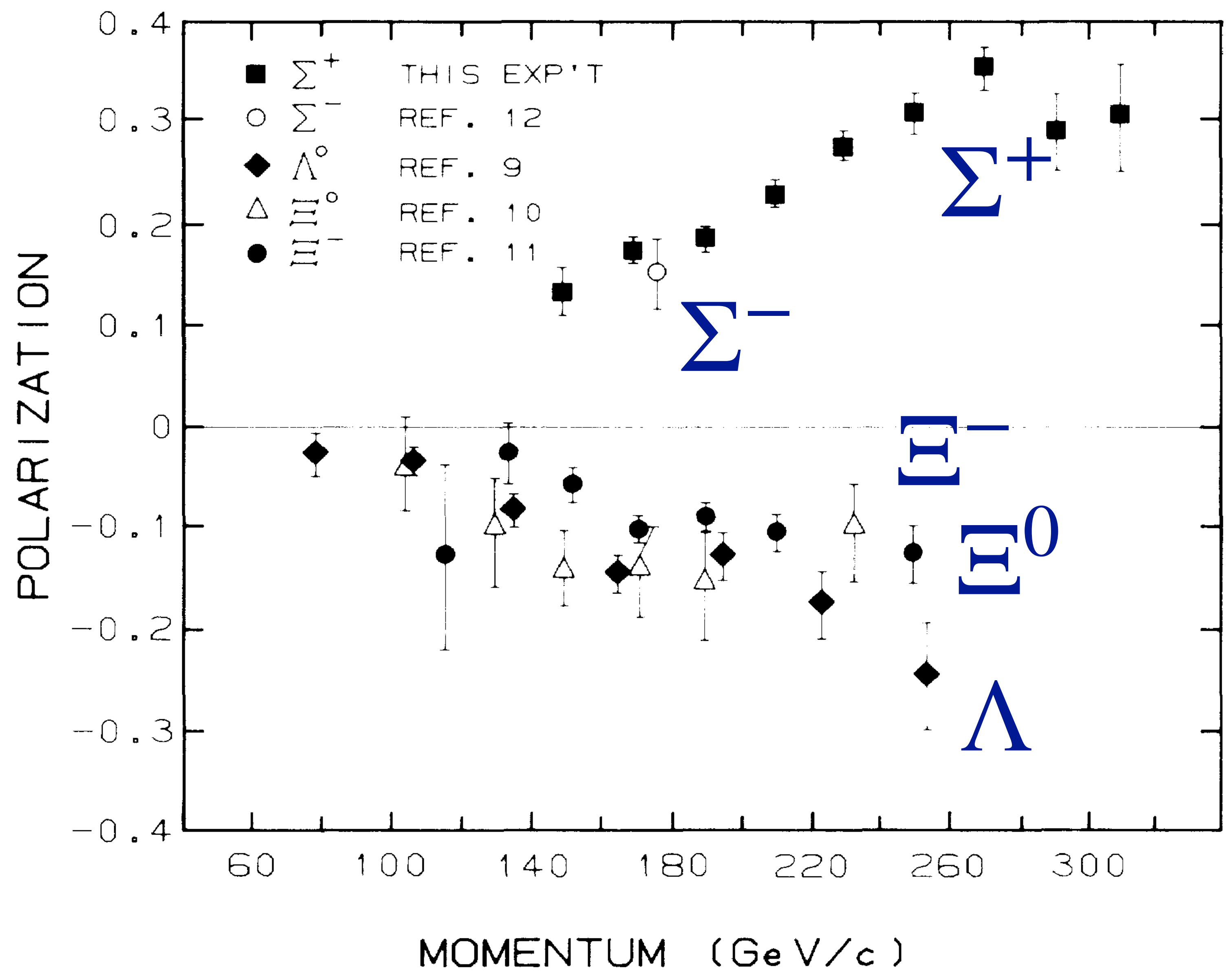
部分实验测量结果

$pp/pA \to \Lambda X$



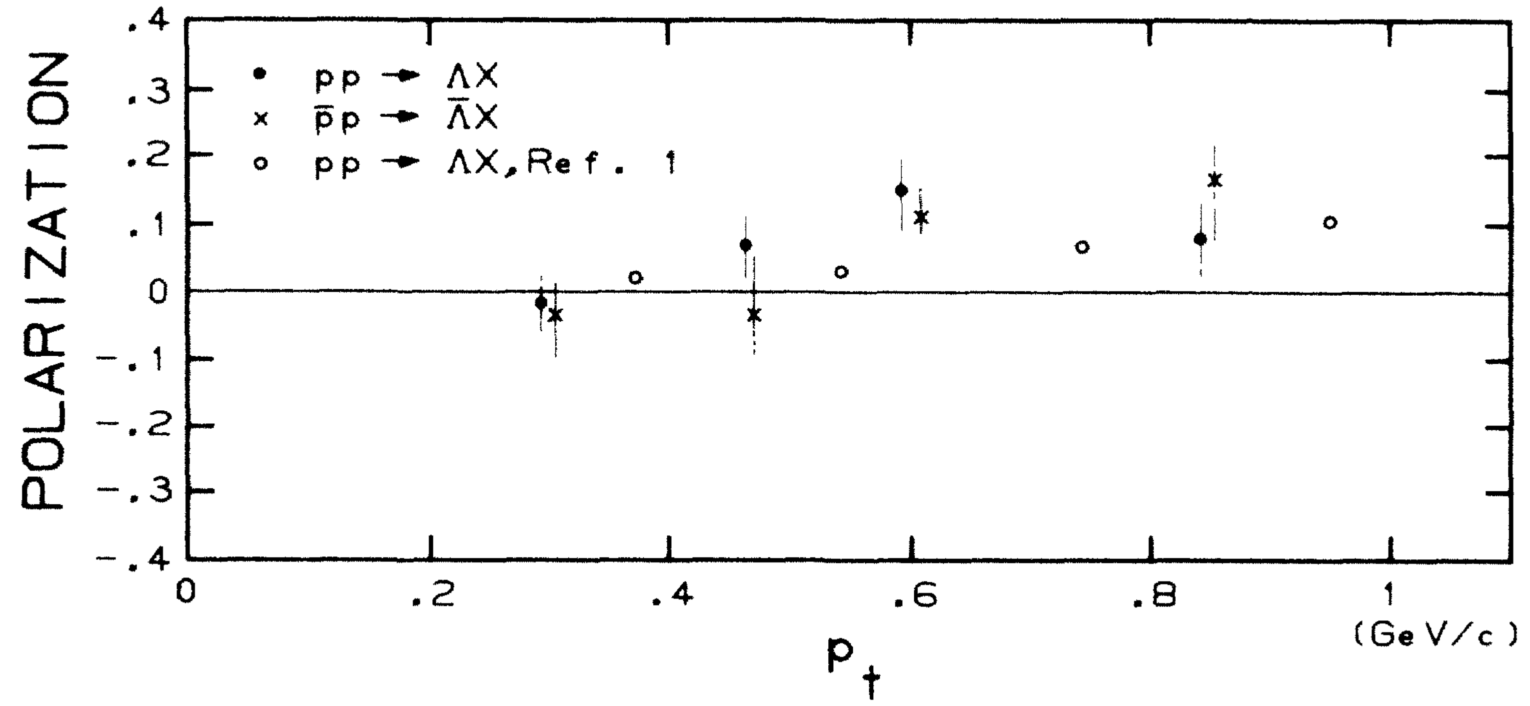
B. Lundberg *et al.*, PRD 40, 1 (1989).

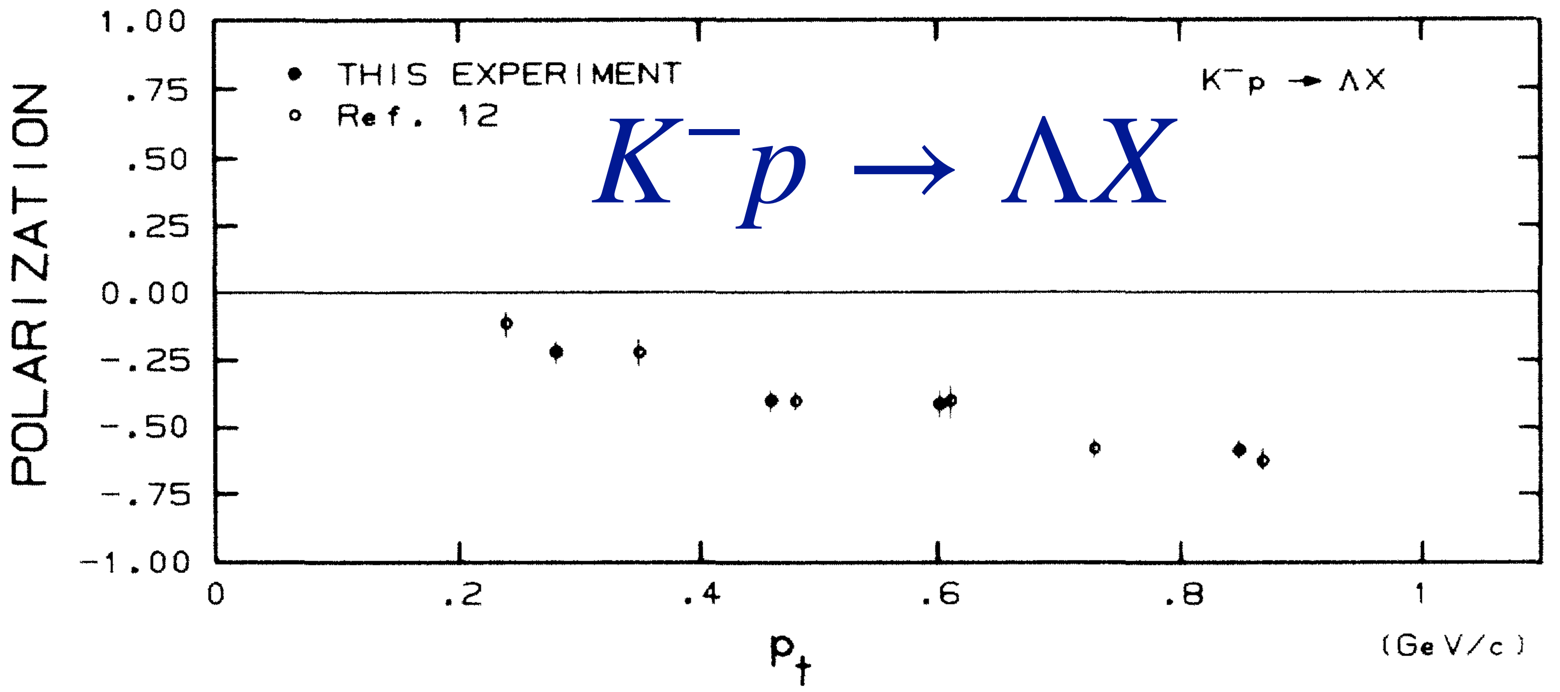
$pp/pA \to HX$



C. Wilkinson *et al.*, PRL 58, 855 (1987).

$pp \to \Lambda X,\ \bar{p}p \to \bar{\Lambda} X$





S.A. Gourlay *et al.*, PRL 56, 2244 (1986).

在大x_F区极化增大

对能量$\sqrt{s}$依赖弱

不同超子极化差异明显

敏感于束流强子种类

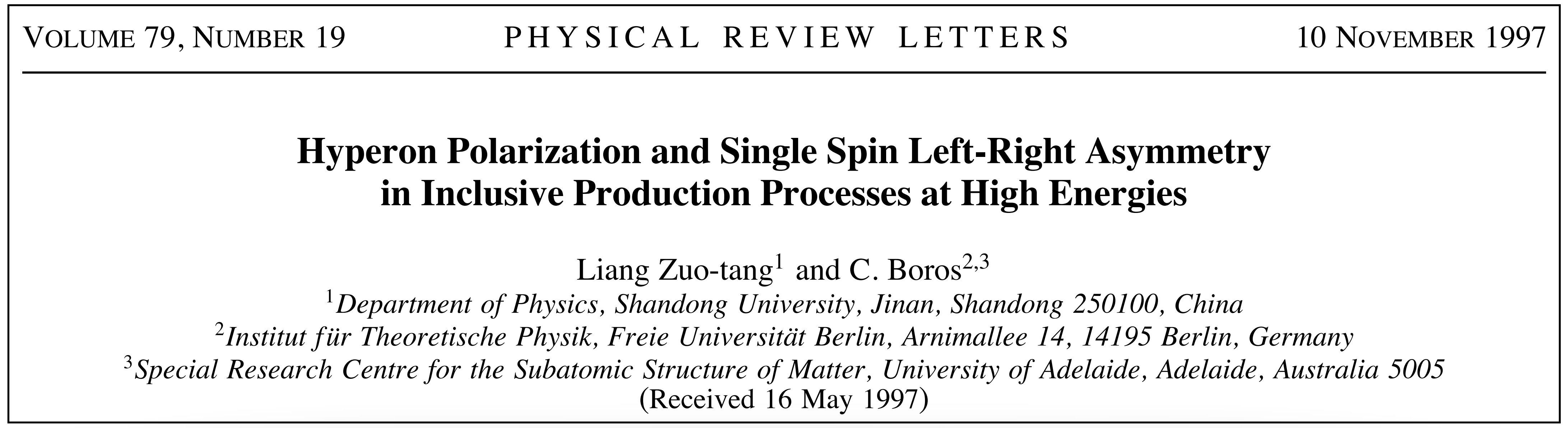
梁-博罗什模型

梁作堂与C. Boros指出：

初态横向极化引发强子产额左右不对称(A_N)

与末态超子横向极化(P_H)的物理机制是同源的

（文献中有时亦称之为“Zuo-tang model”）



VOLUME 79, NUMBER 19 PHYSICAL REVIEW LETTERS 10 NOVEMBER 1997

Hyperon Polarization and Single Spin Left-Right Asymmetry in Inclusive Production Processes at High Energies

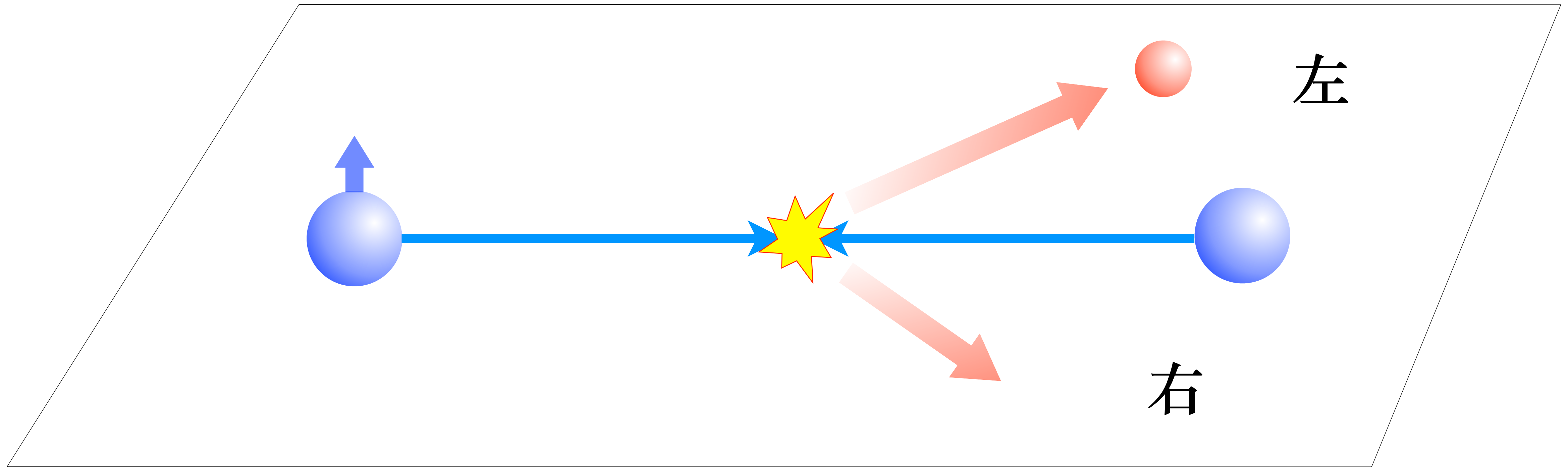
Liang Zuo-tang[1] and C. Boros[2,3]

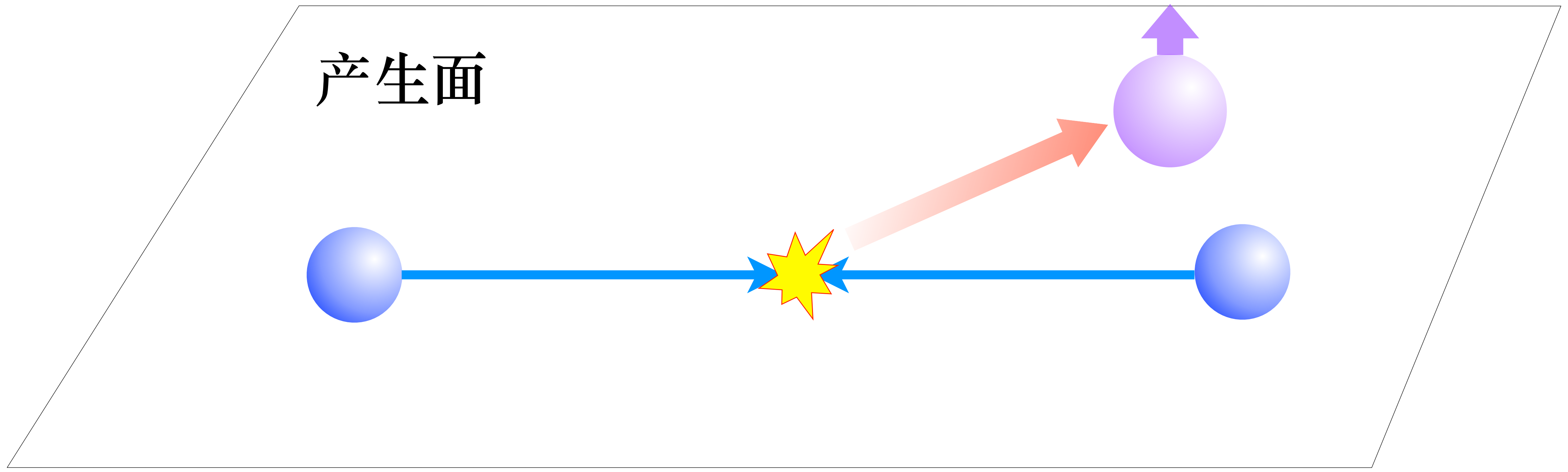
[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*

[2]*Institut für Theoretische Physik, Freie Universität Berlin, Arnimallee 14, 14195 Berlin, Germany*

[3]*Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Adelaide, Australia 5005*

(Received 16 May 1997)





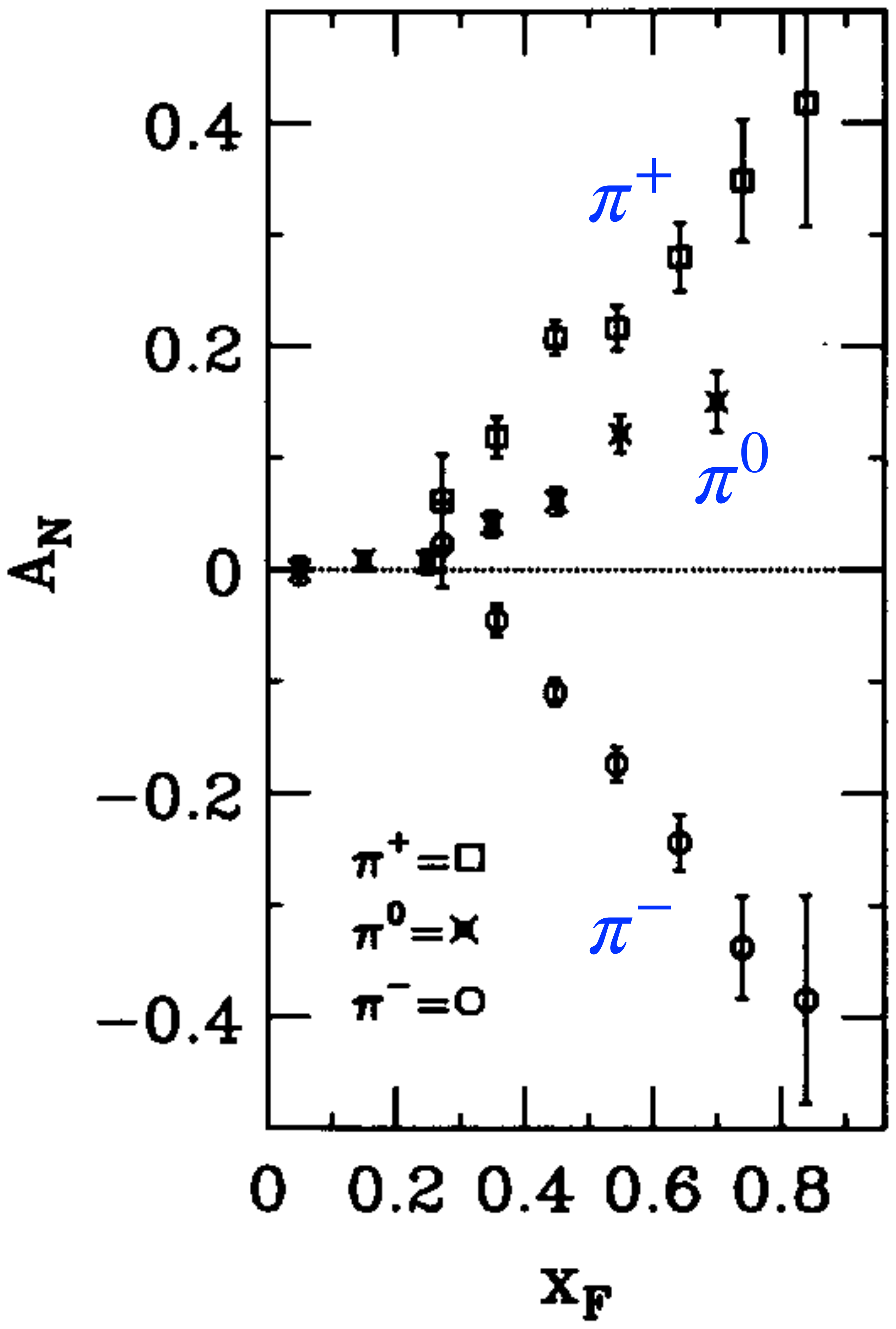
夸克横向自旋选择横向动量倾向

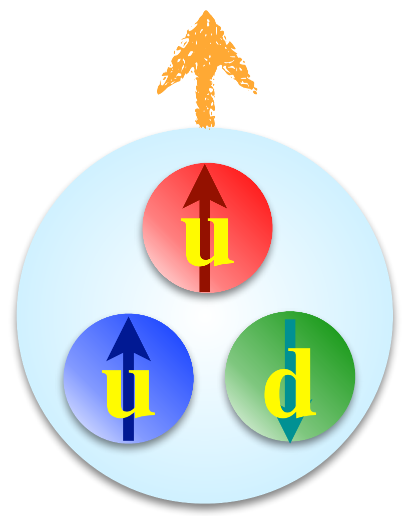
夸克横向动量选择横向自旋倾向

夸克横向自旋与横向动量的关联效应

梁-博罗什模型

$p^{\uparrow}p \to \pi X$





$$|p_{\uparrow}\rangle = \frac{1}{\sqrt{18}}\Big[2\,|u_{\uparrow}d_{\downarrow}u_{\uparrow}\rangle + 2\,|u_{\uparrow}u_{\uparrow}d_{\downarrow}\rangle + 2\,|d_{\downarrow}u_{\uparrow}u_{\uparrow}\rangle - |u_{\uparrow}u_{\downarrow}d_{\uparrow}\rangle - |u_{\uparrow}d_{\uparrow}u_{\downarrow}\rangle - |u_{\downarrow}d_{\uparrow}u_{\uparrow}\rangle - |d_{\uparrow}u_{\downarrow}u_{\uparrow}\rangle - |d_{\uparrow}u_{\uparrow}u_{\downarrow}\rangle - |u_{\downarrow}u_{\uparrow}d_{\uparrow}\rangle\Big].$$

u夸克向上(与质子同向)极化，d夸克向下(与质子反向)极化

强子产额 $\pi^{+}(u\bar{d})$ 倾向左侧，$\pi^{-}(d\bar{u})$ 倾向右侧

初态自旋向上u夸克倾向向左，自旋向下d夸克倾向向右

末态u, d夸克相对于产生面倾向于自旋向上

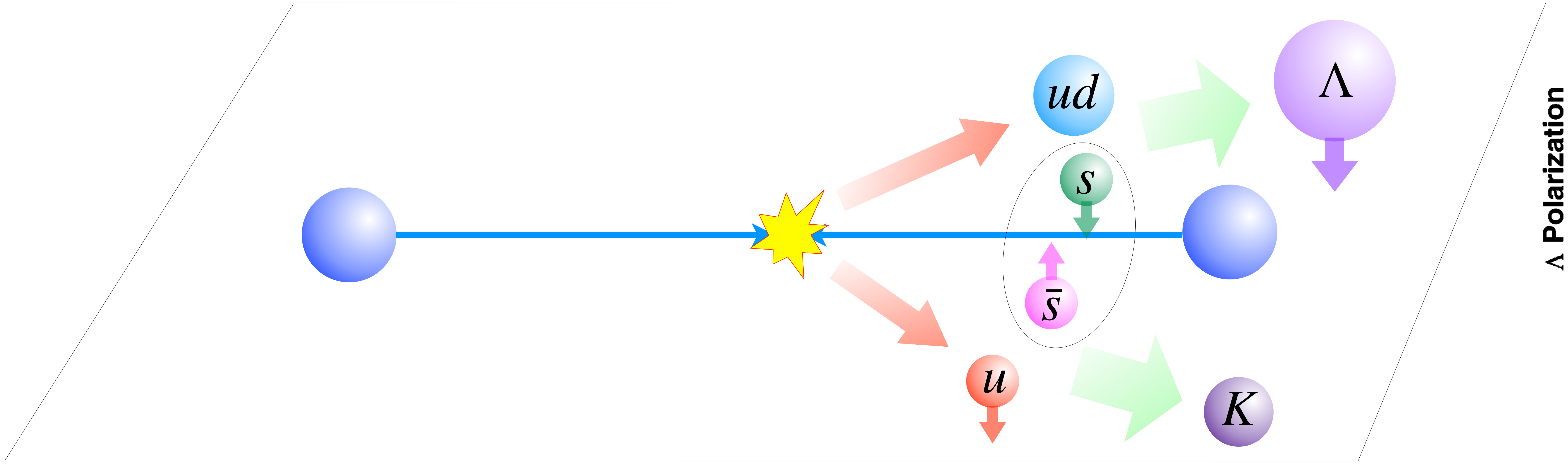
梁-博罗什模型

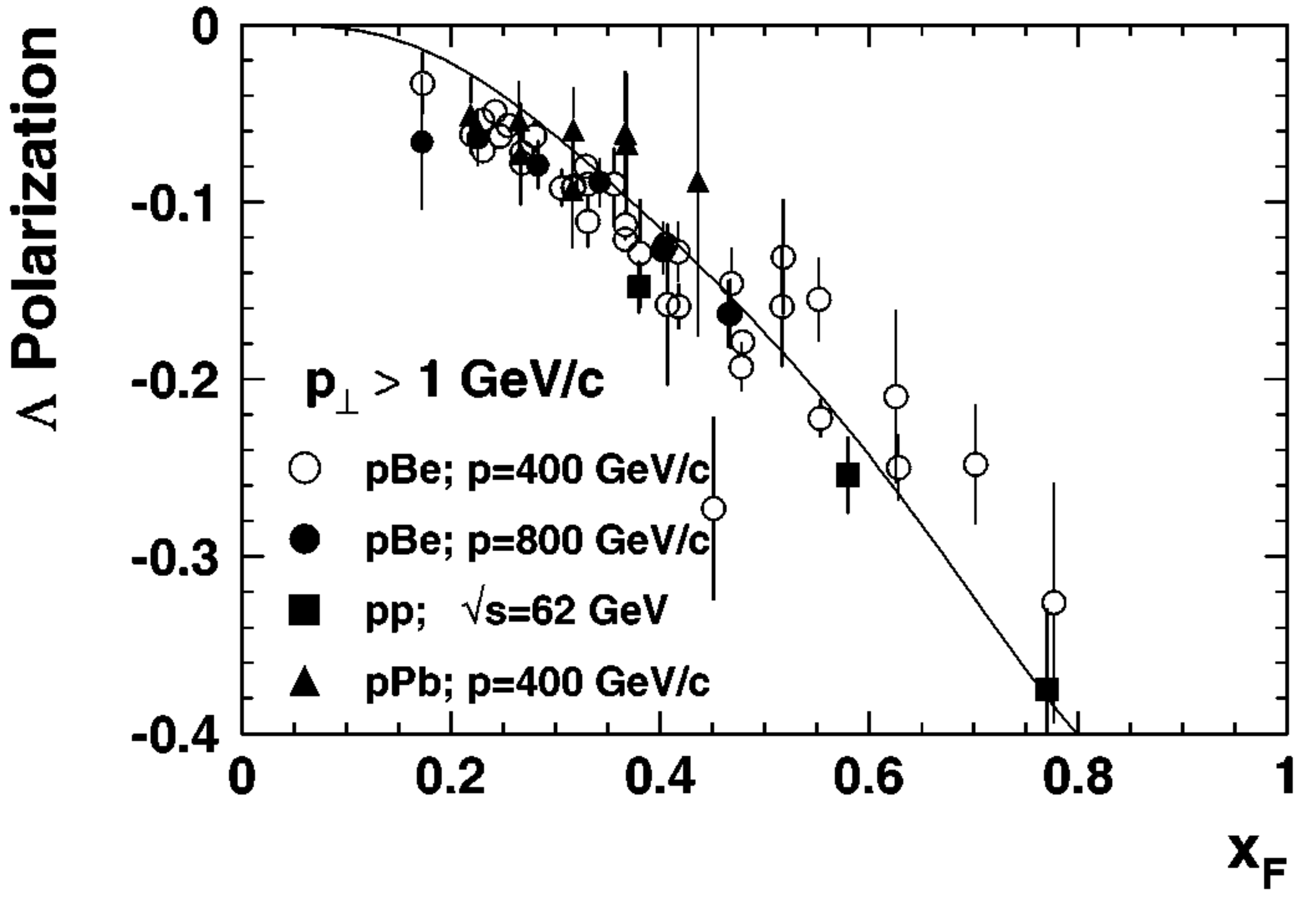
ud 双夸克碎裂为 Λ 的反应道，在 Λ 产生的另一侧有倾向于自旋向下的夸克

海中的 s 与 $\bar{s}$ 横向自旋反关联

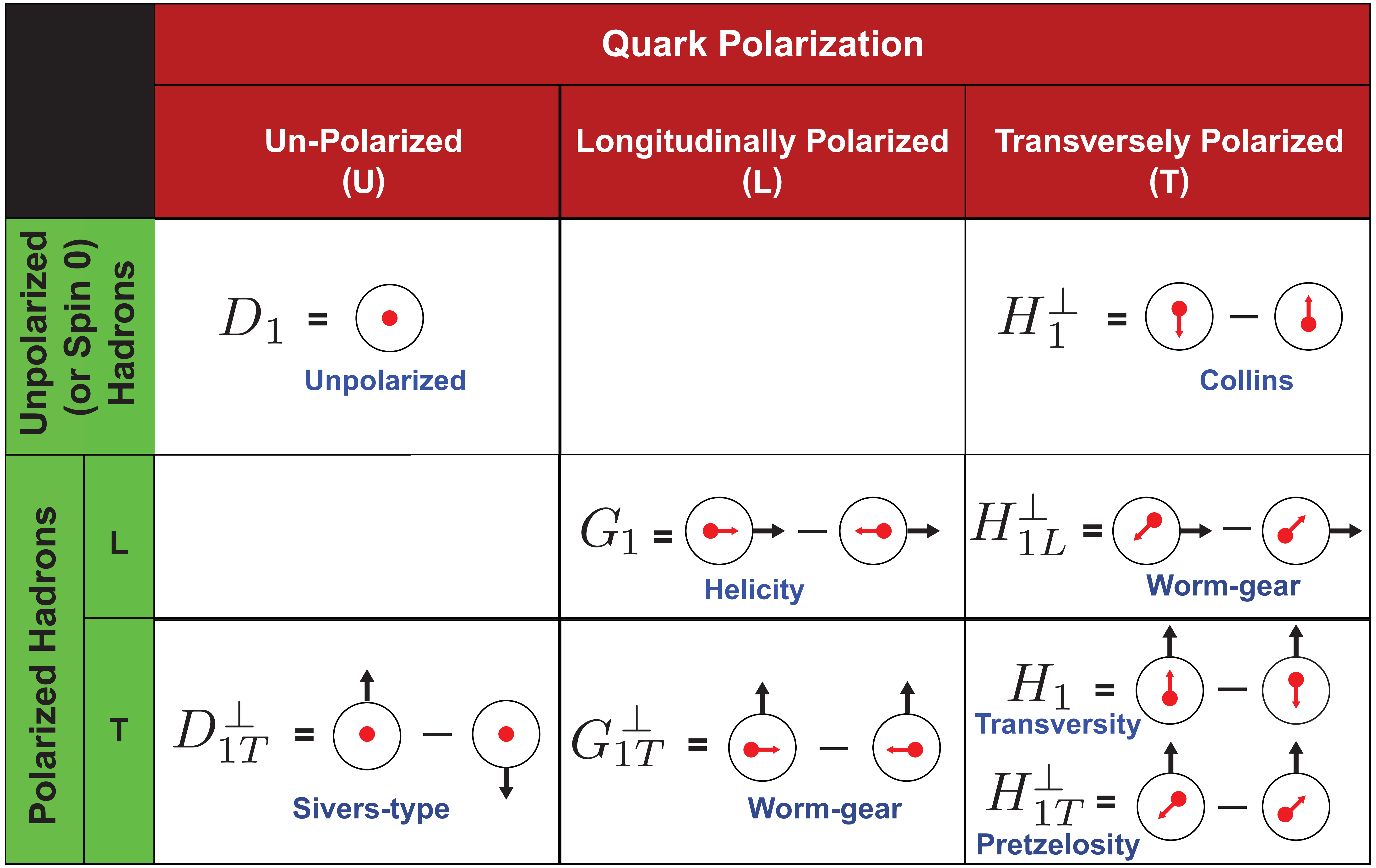
伴随 K 介子产生倾向挑选自旋向上的 $\bar{s}$ 夸克

与 ud 双夸克组合的 s 夸克更多为自旋向下，自旋转移为 Λ 超子向下极化





自旋-横动量依赖的碎裂函数

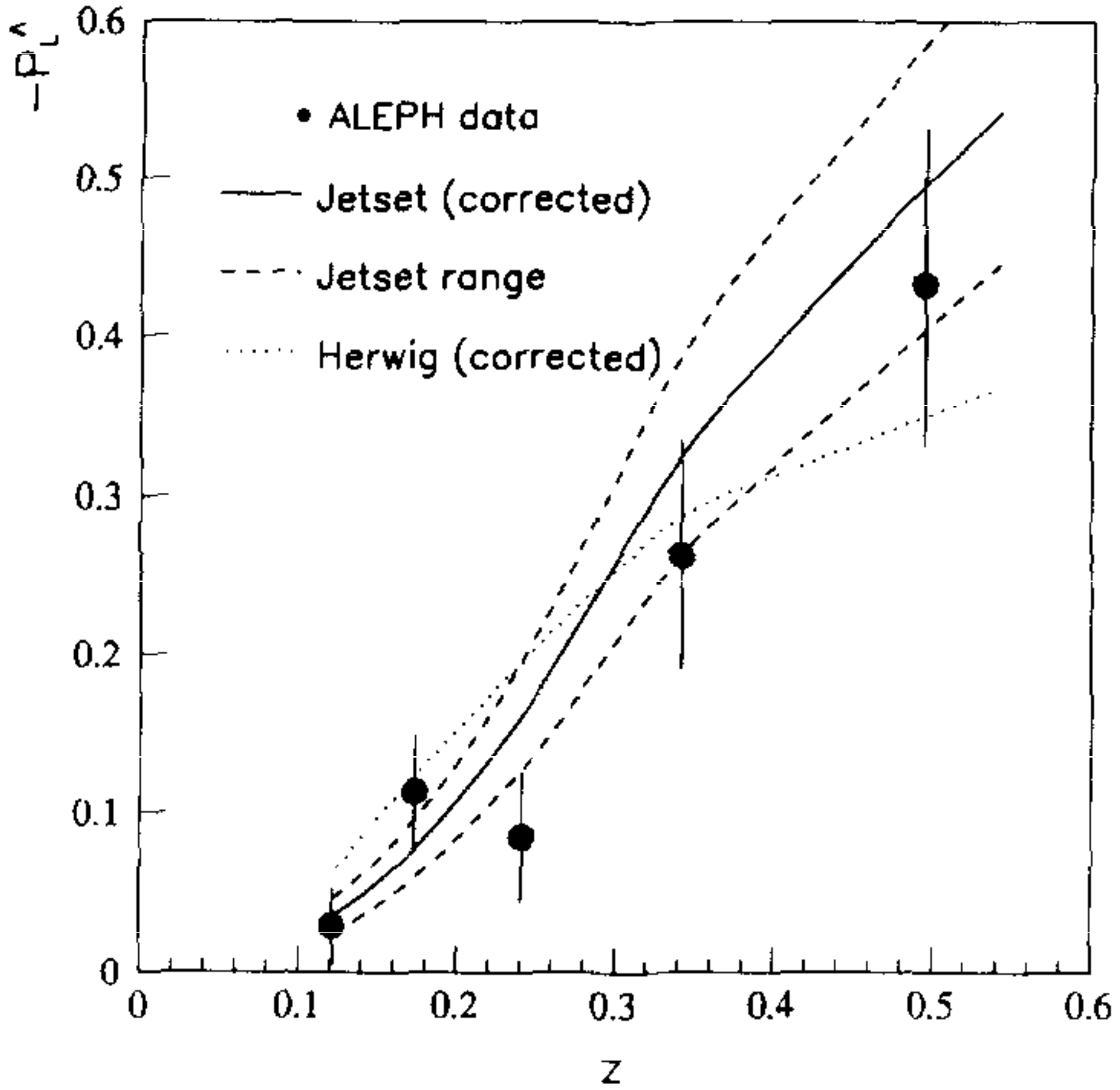


[Figure from TMD Handbook]

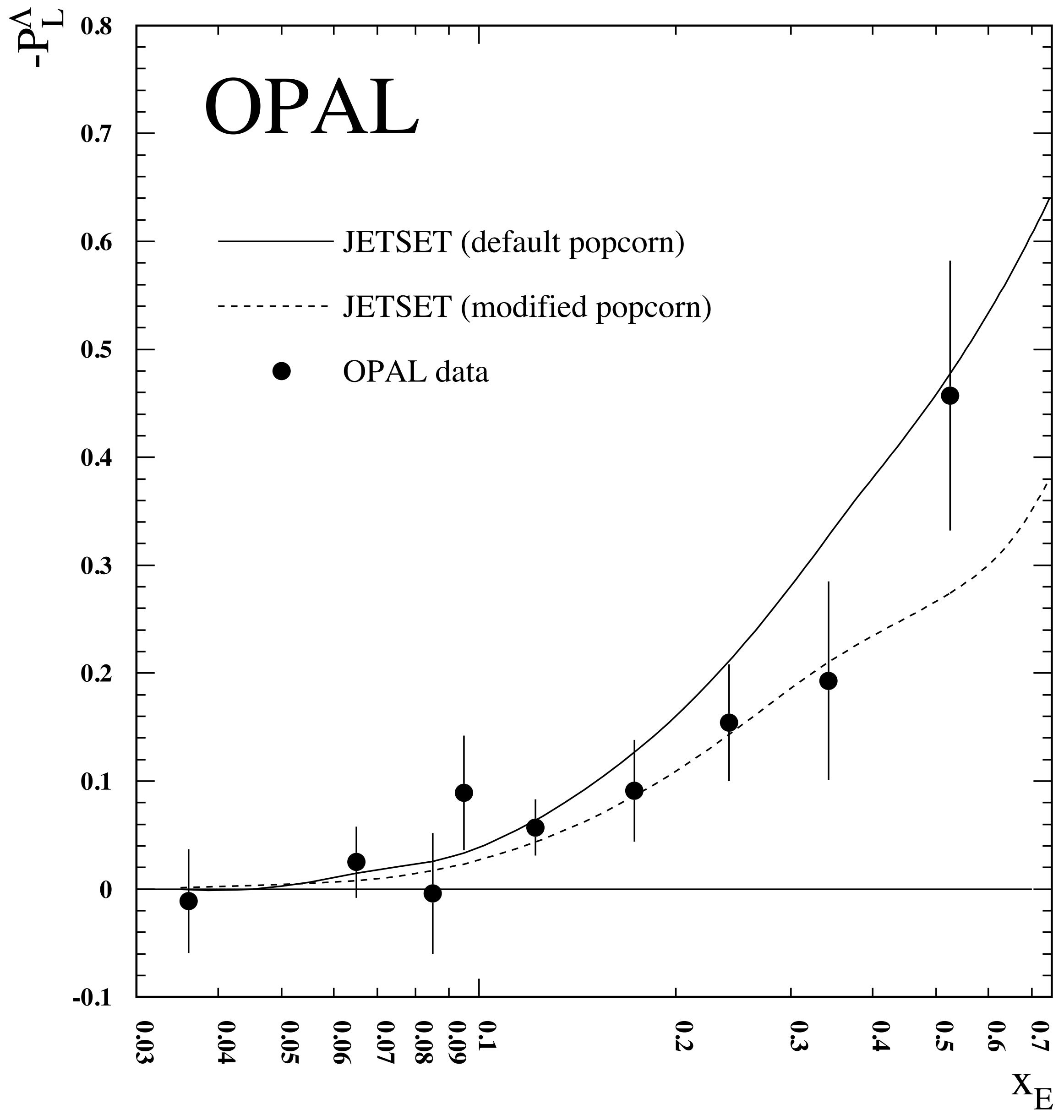
夸克碎裂过程的自旋转移

正负电子湮灭过程

$$e^+e^- \to Z^0 \to \Lambda X$$



ALEPH Collaboration, Phys. Lett. B 374 (1996) 319.



OPAL Collaboration, Eur. Phys. J. C 2 (1998) 49.

通过弱中性流作用产生极化夸克，测得夸克碎裂到Λ超子过程的自旋转移

夸克碎裂过程的自旋转移

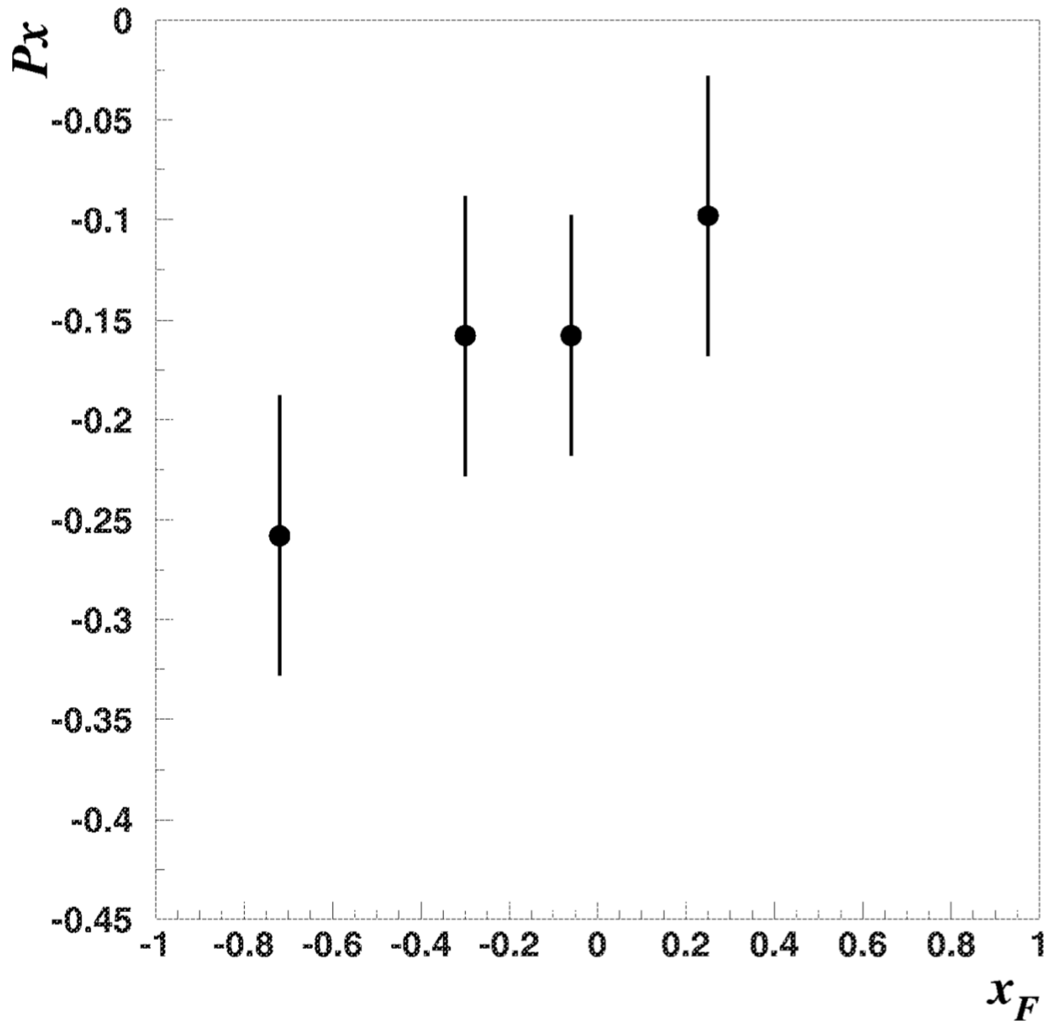
中微子散射过程

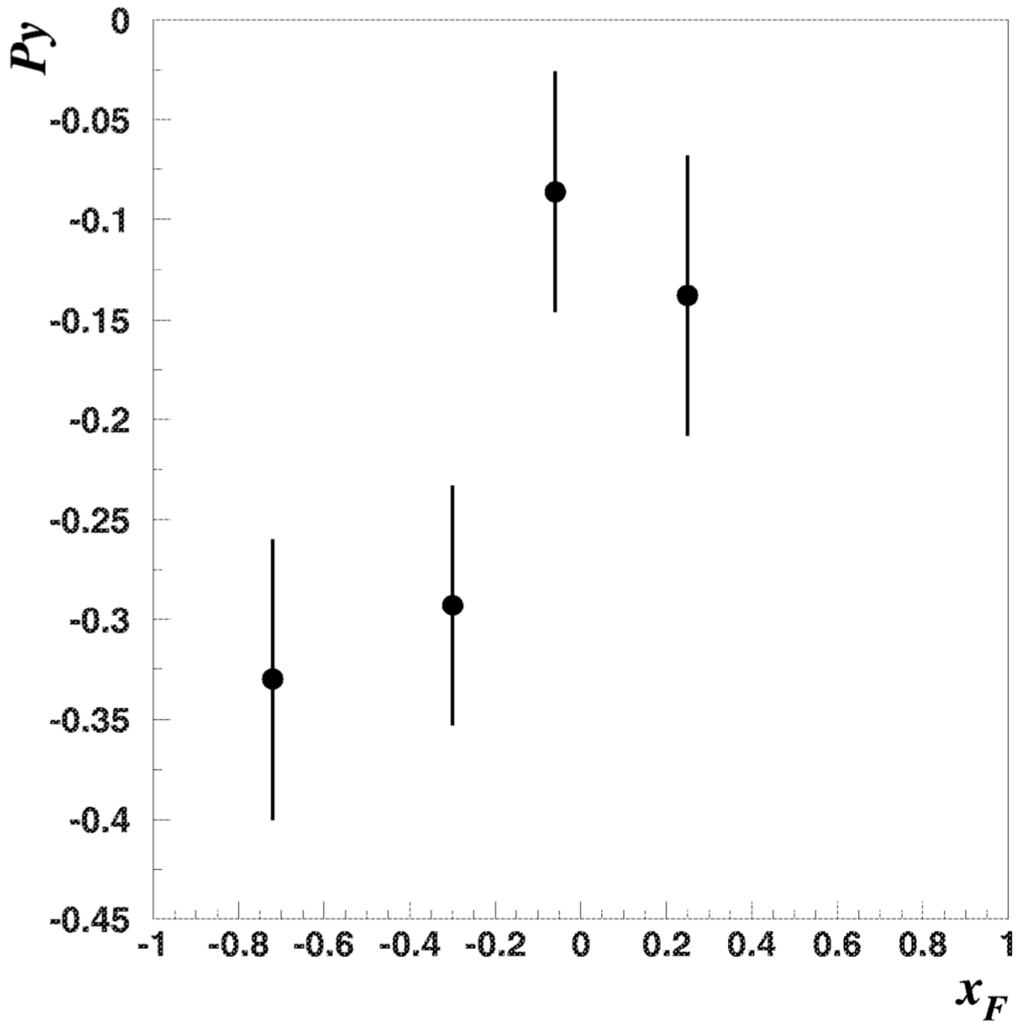
G.T. Jones *et al.* Birmingham-Bonn-CERN-London-Munich-Oxford, Z. Phys. C 28 (1985) 23.
WA59 Collaboration, Z. Phys. C 53 (1992) 207.
E632 Collaboration, Phys. Rev. D 50 (1994) 6691.
NOMAD Collaboration, Nucl. Phys. B 588 (2000) 3.
NOMAD Collaboration, Nucl. Phys. B 605 (2001) 3.

TABLE VI. Λ Polarization. The x axis is along the W boson direction in the Λ rest frame. The other two axes are perpendicular to the W, with the y axis being transverse to the production plane, and the z axis inside the production plane.

Reaction [Ref.]	P_x	P_y	P_z
ν-Ne [This expt.]	-0.38 ± 0.16	-0.04 ± 0.17	-0.17 ± 0.18
$\bar{\nu}$-Ne [15]	-0.56 ± 0.13	-0.02 ± 0.13	0.08 ± 0.13
ν-p [26]	-0.10 ± 0.14	-0.02 ± 0.16	0.12 ± 0.15
$\bar{\nu}$-p [26]	-0.24 ± 0.17	-0.05 ± 0.16	-0.20 ± 0.17
ν-Ne, $x_F < 0$ [This expt.]	-0.43 ± 0.20	-0.06 ± 0.19	-0.45 ± 0.19
$\bar{\nu}$-Ne, $x_F < 0$ [15]	-0.63 ± 0.13	-0.02 ± 0.14	0.12 ± 0.14
ν-p, $x_F < 0$ [26]	-0.29 ± 0.18	-0.09 ± 0.19	0.19 ± 0.18
$\bar{\nu}$-p, $x_F < 0$ [26]	-0.38 ± 0.18	0.02 ± 0.18	-0.17 ± 0.18
K^0 control sample [This expt.]	-0.02 ± 0.08	0.10 ± 0.08	-0.10 ± 0.08

E632 Collaboration, Phys. Rev. D 50 (1994) 6691.



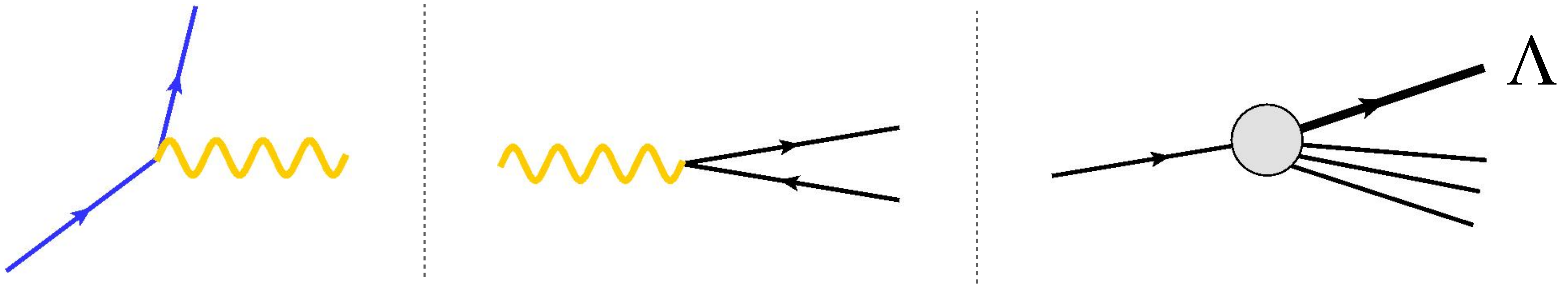


NOMAD Collaboration, Nucl. Phys. B 588 (2000) 3.

通过弱带电流作用产生极化夸克，测得夸克碎裂到Λ超子过程的自旋转移

夸克碎裂过程的自旋转移

极化带电轻子束流散射过程 $e^{\uparrow}p \rightarrow e\Lambda^{\uparrow}X$

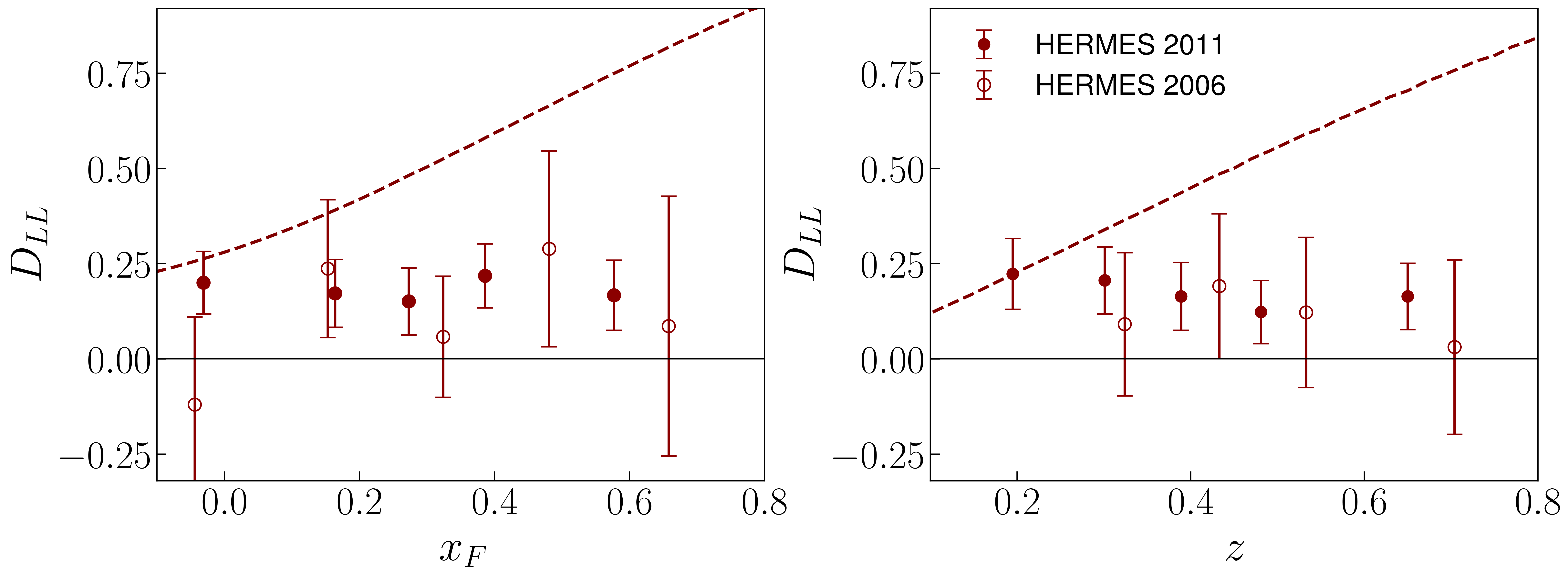


产生极化虚光子　　出射夸克极化　　碎裂过程自旋转移

预期末态 Λ 超子将具有很高的极化度

夸克碎裂过程的自旋转移

极化带电轻子束流散射过程 $e^{\uparrow}p \to e\Lambda^{\uparrow}X$

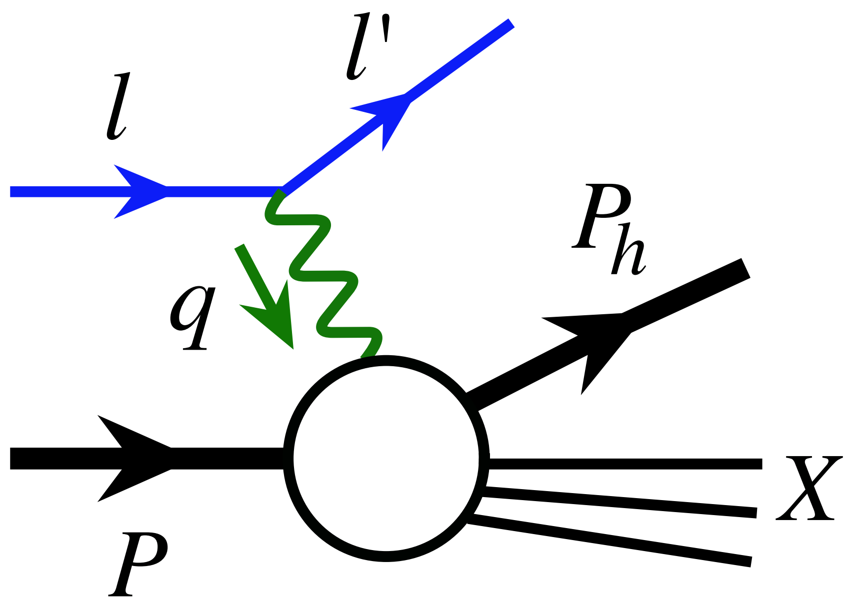


实验测得自旋转移信号远低于理论预期

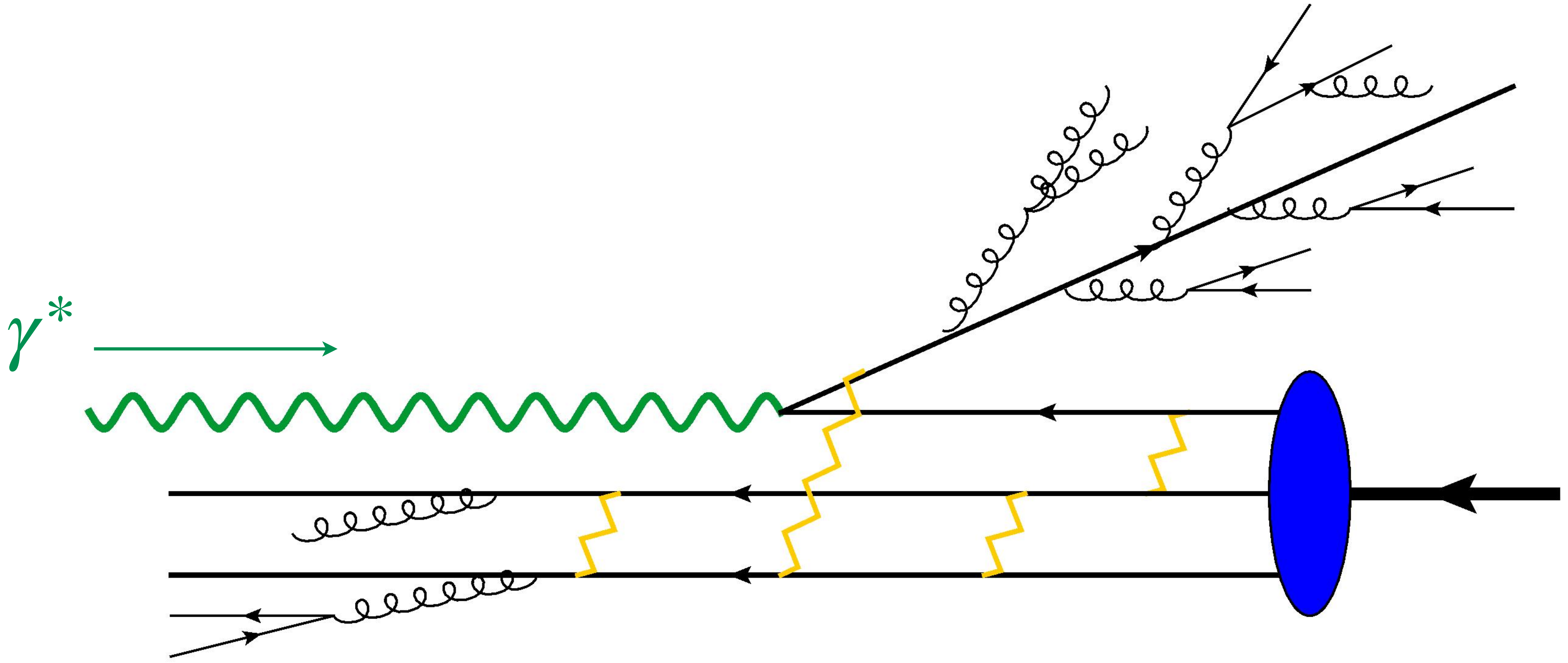
重新审视Λ超子产生来源

实验事实：末态产生Λ超子，其运动学分布与极化度

理论假设：Λ超子主要源于被虚光子撞击夸克的碎裂过程



理想情形：

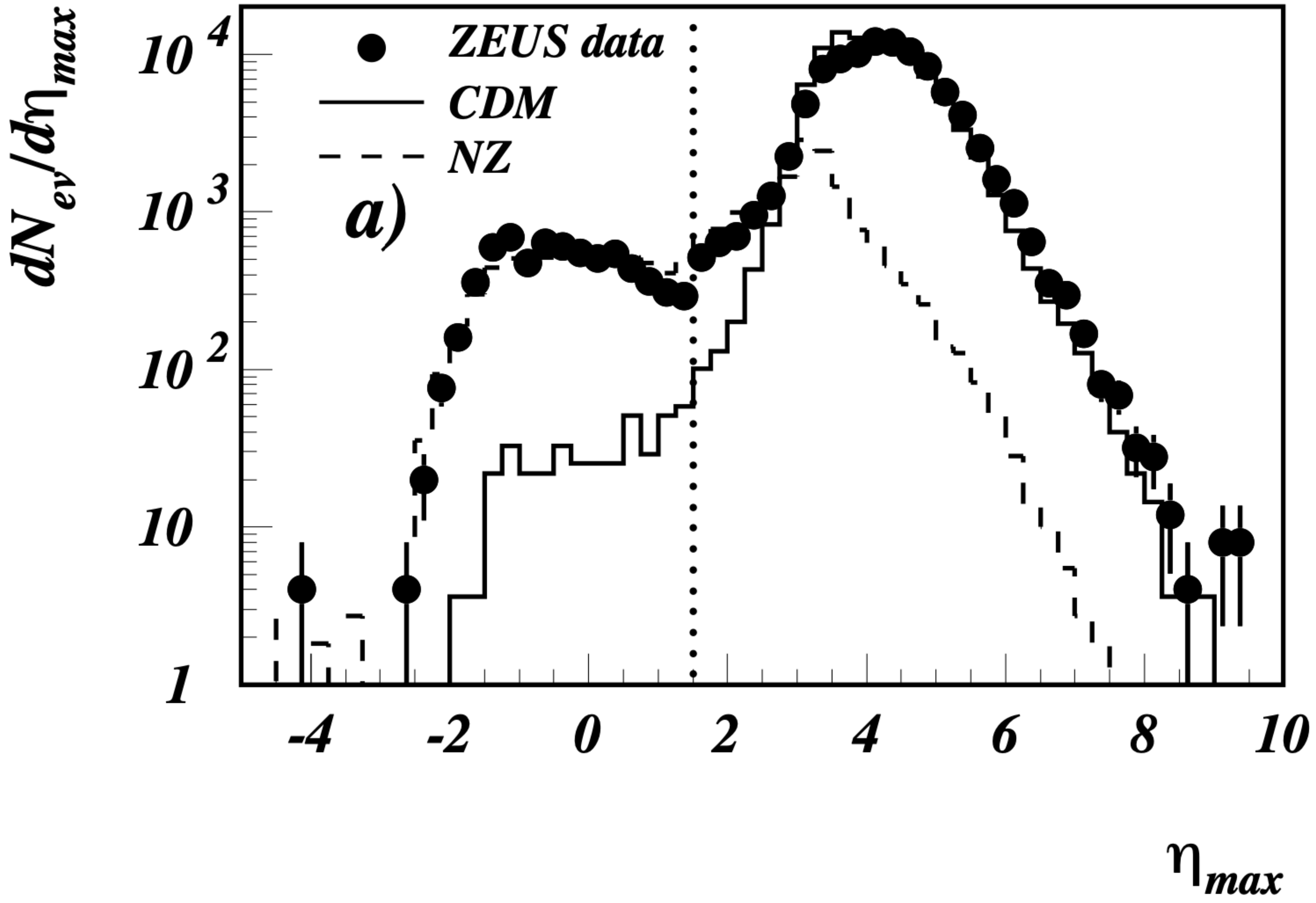


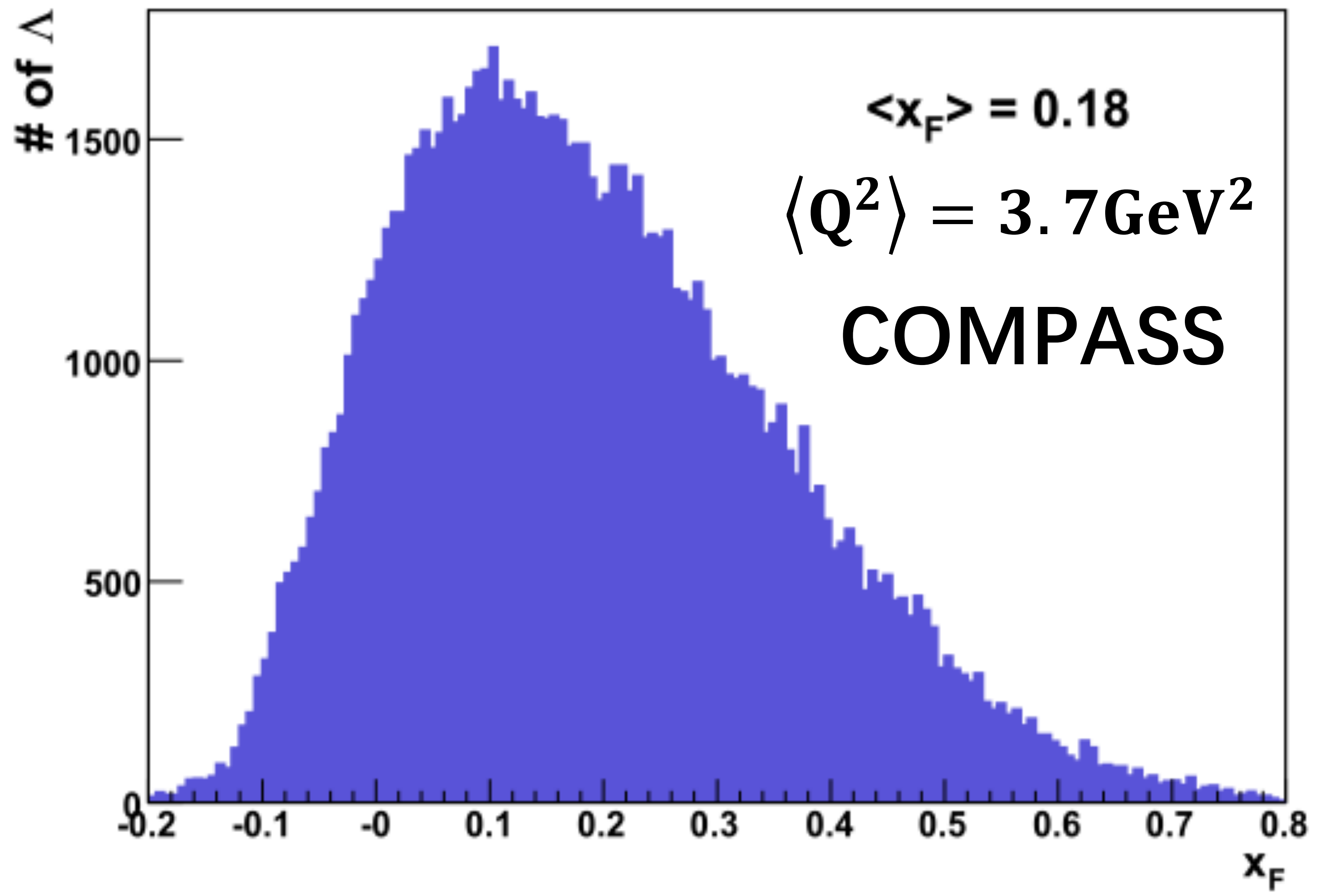
在高能极限，绝大部分能量传递给被撞击的夸克，且有足够大的相空间

末态强子主要来自被撞击夸克的碎裂，与靶碎裂产生强子在快度上分离

重新审视Λ超子产生来源

现实情形：



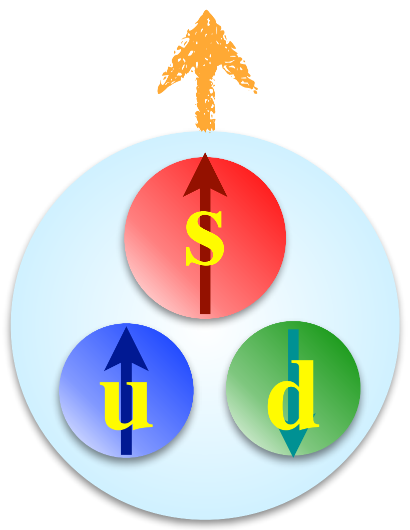


在HERA能量观测到流碎裂主导
以及与靶碎裂在快度上的分离

现有能量固定靶实验未见到
流碎裂与靶碎裂运动学界限

靶碎裂机制与Λ自旋转移

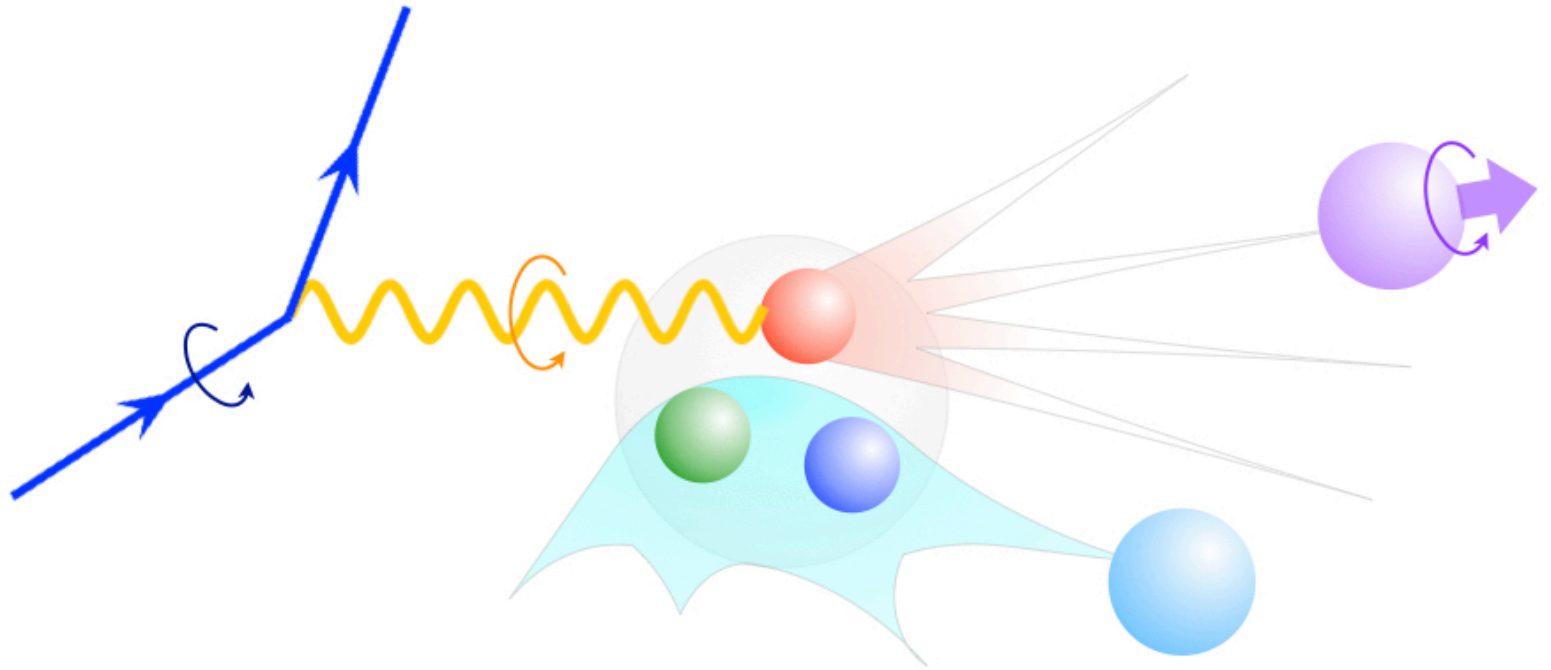
自旋味道结构分析



$$\Lambda^{\uparrow} = \frac{1}{\sqrt{3}}(ud)_{0,0}s^{\uparrow} + \frac{1}{\sqrt{12}}(us)_{0,0}d^{\uparrow} - \frac{1}{\sqrt{12}}(ds)_{0,0}u^{\uparrow}$$
$$+ \frac{1}{2}\left(\sqrt{\frac{2}{3}}(us)_{1,1}d^{\downarrow} - \sqrt{\frac{1}{3}}(us)_{1,0}d^{\uparrow}\right) - \frac{1}{2}\left(\sqrt{\frac{2}{3}}(ds)_{1,1}u^{\downarrow} - \sqrt{\frac{1}{3}}(ds)_{1,0}u^{\uparrow}\right)$$

结合核子的夸克分布

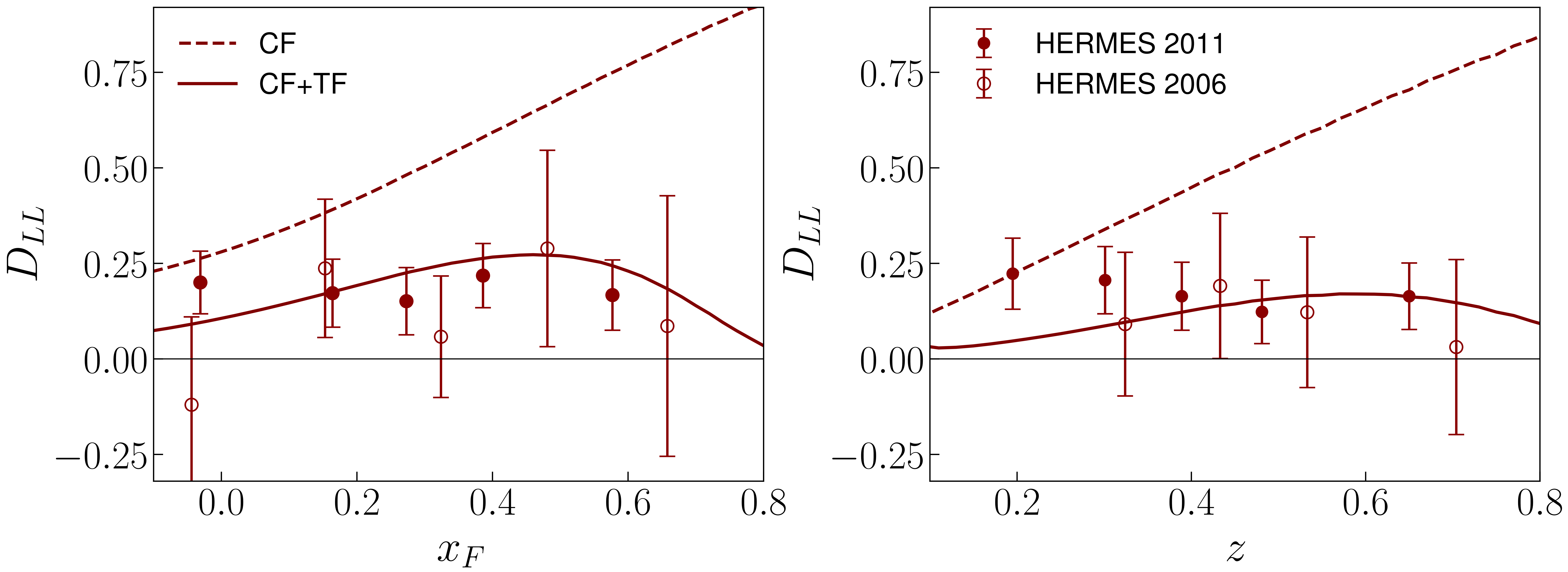
$$u, d > \bar{u}, \bar{d} > s, \bar{s}$$



核子剩余部分的标量ud夸克对为靶碎裂主要贡献

靶碎裂贡献将显著压低末态Λ超子的自旋转移信号

理论预期与已有实验数据的比较



Xiaoyan Zhao, Zuo-tang Liang, Tianbo Liu, Ya-jin Zhou, PRL 134 (2025) 231901.

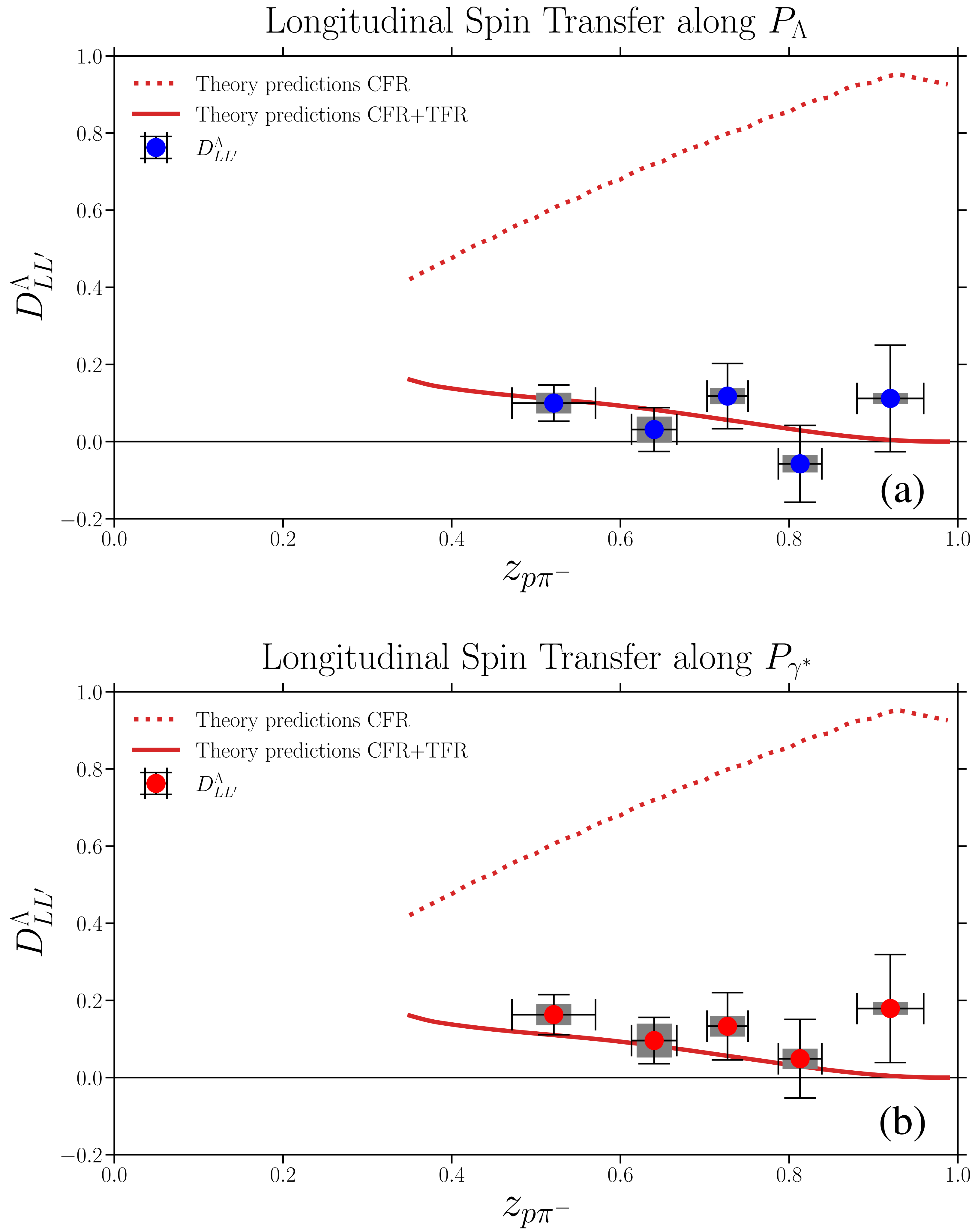
进一步实验验证

JLab-CLAS实验组

PHYSICAL REVIEW D **113**, 092019 (2026)

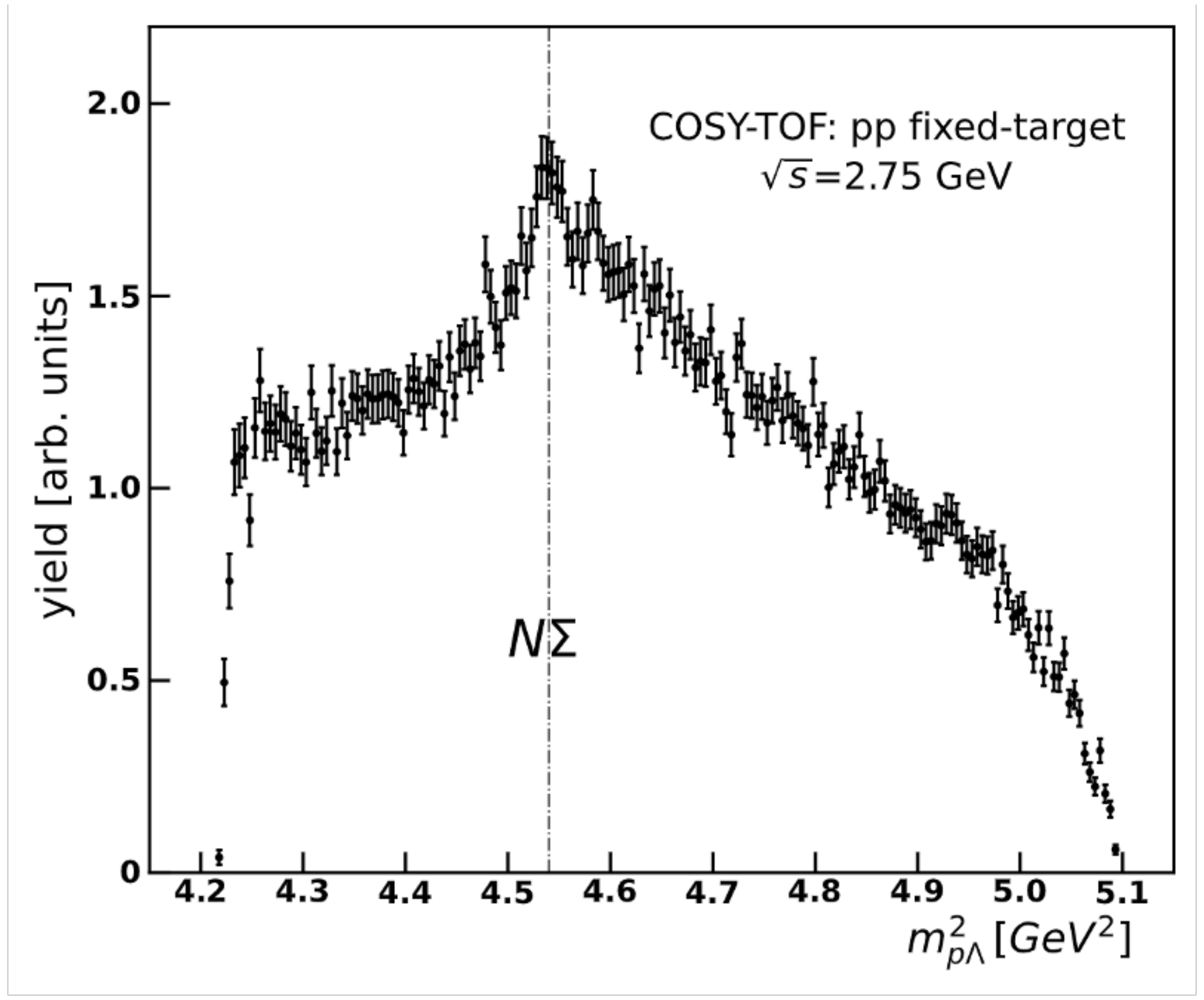
Longitudinal spin transfer to Λ hyperons in semi-inclusive deep inelastic scattering with the CLAS12 spectrometer

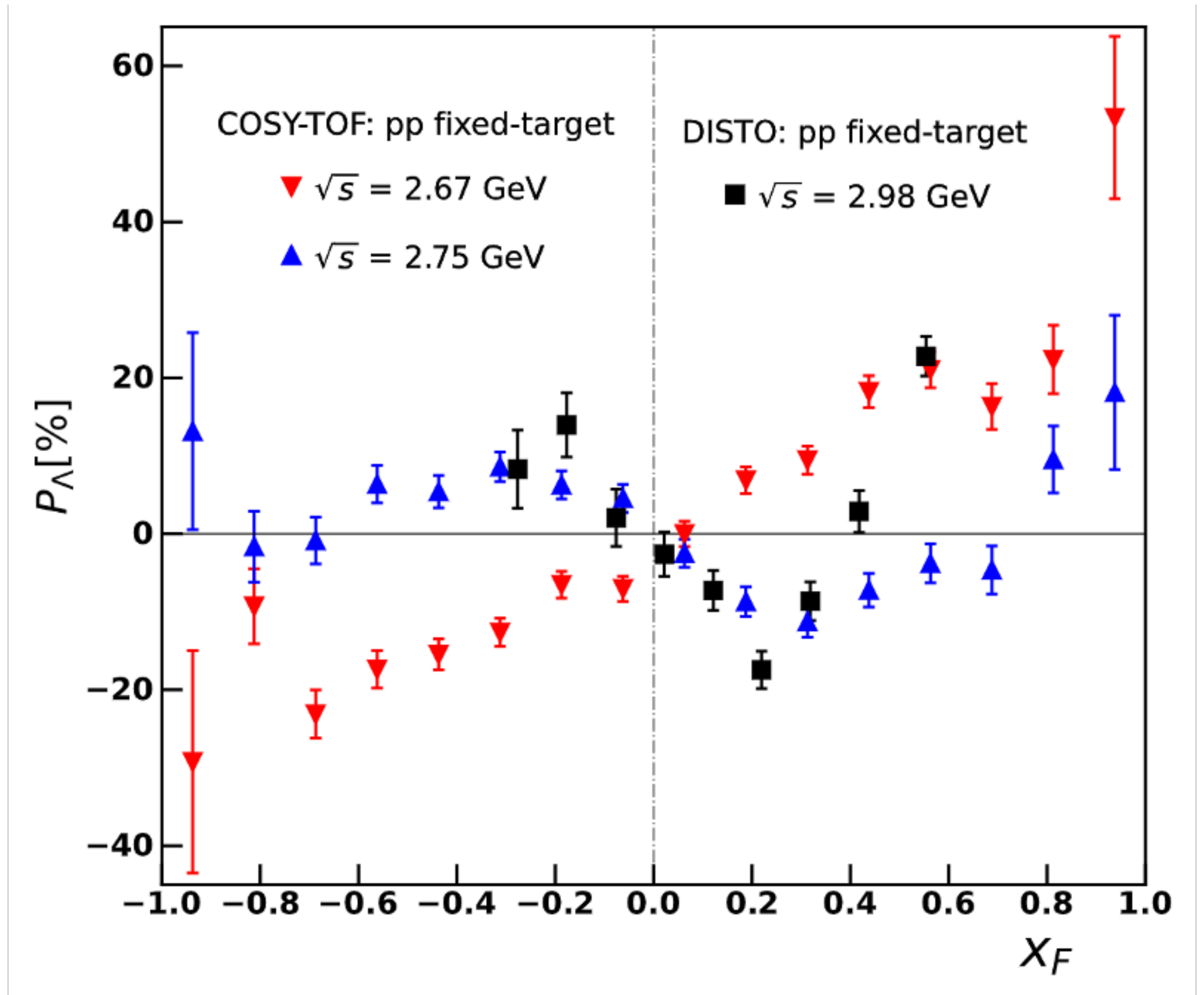
There is also a dilution effect from TFR Λs that form from the remnant diquark system in the target nucleon. Λs originating from the TFR should not carry any spin transfer since the electron spin is only imparted to the struck diquark. Hence, one expects TFR contributions to have zero spin transfer and to dilute any spin transfer from the CFR. Since the $x_{Fp\pi^-} > 0$ cut does not guarantee that the sample is purely CFR Λs, our results may be affected by some inevitable contamination from the TFR, and this is in fact observed by comparison with theory predictions [39] including both CFR and TFR contributions as shown in Figs. 9 and 10. The CFR predictions were obtained with



$pp \to pK^+\Lambda$遍举过程超子产生与极化

$\sqrt{s}$ 与HIAF H-NS能量相近



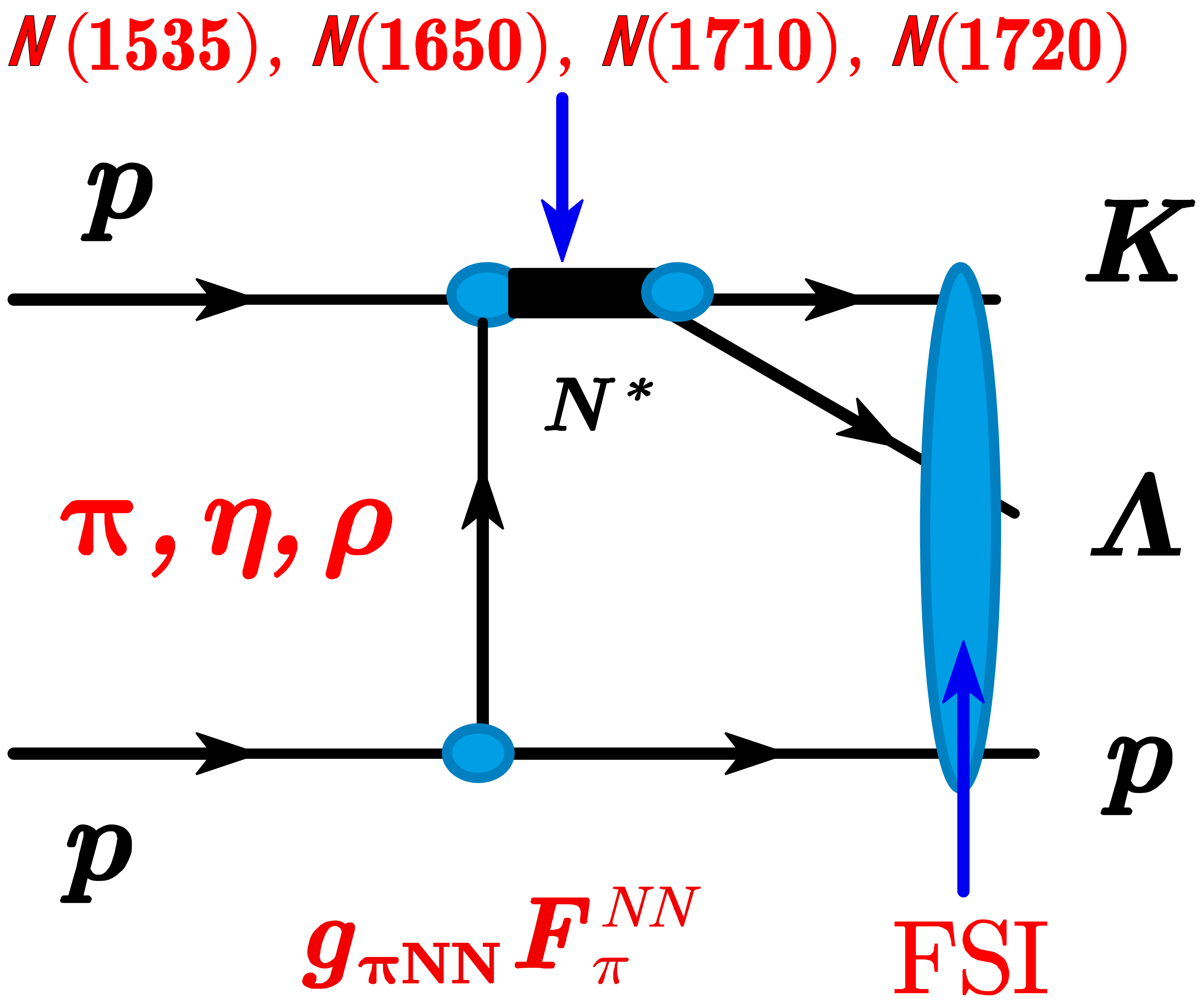


COSY-TOF Collaboration, EPJA 52, 337 (2016).

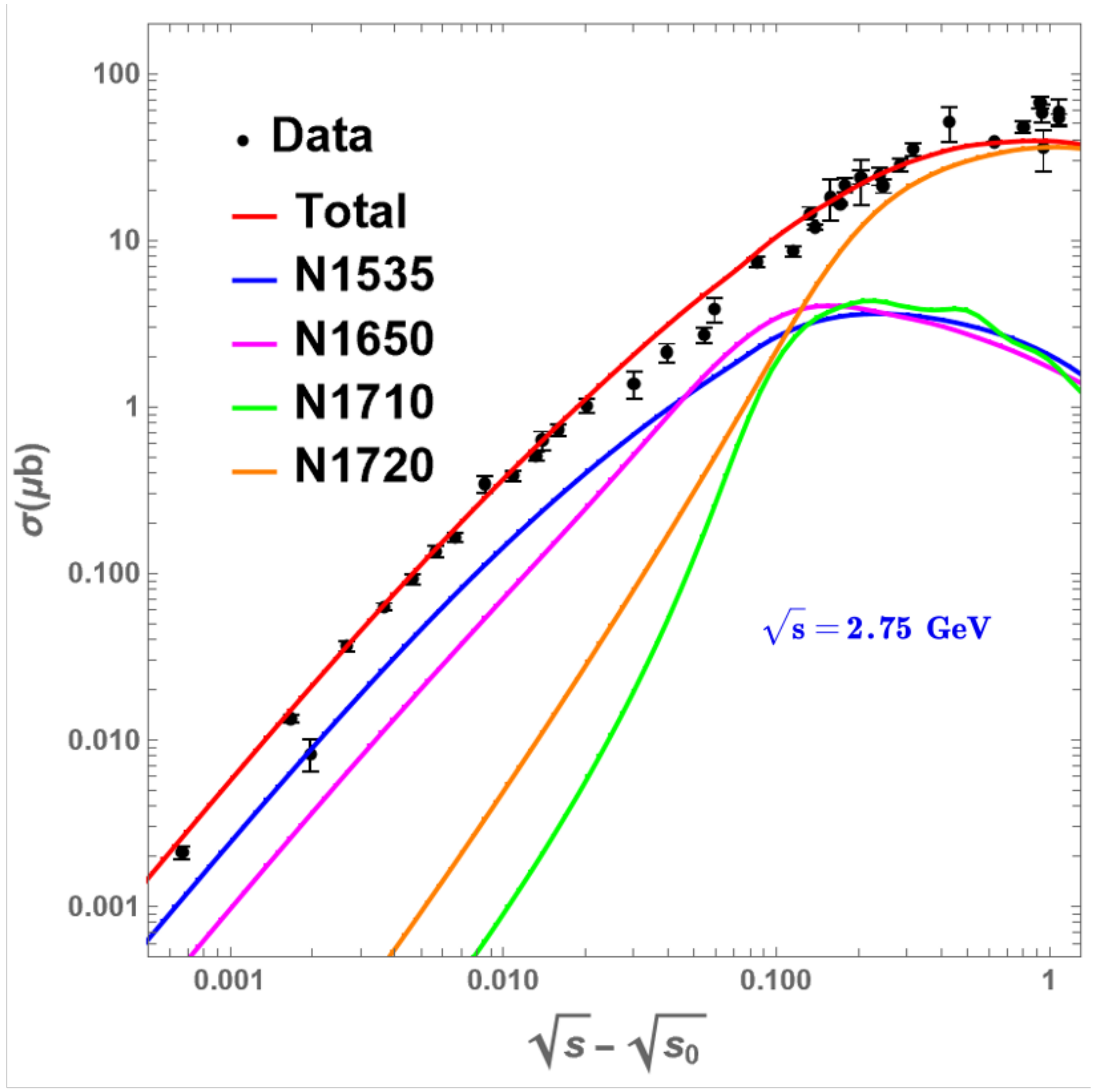
产生截面在近阈处明显增强，Λ超子极化对能量依赖敏感

超子-核子存在显著末态相互作用，产生过程受共振态贡献影响

$pp \to pK^+\Lambda$过程的介子交换模型计算



总截面

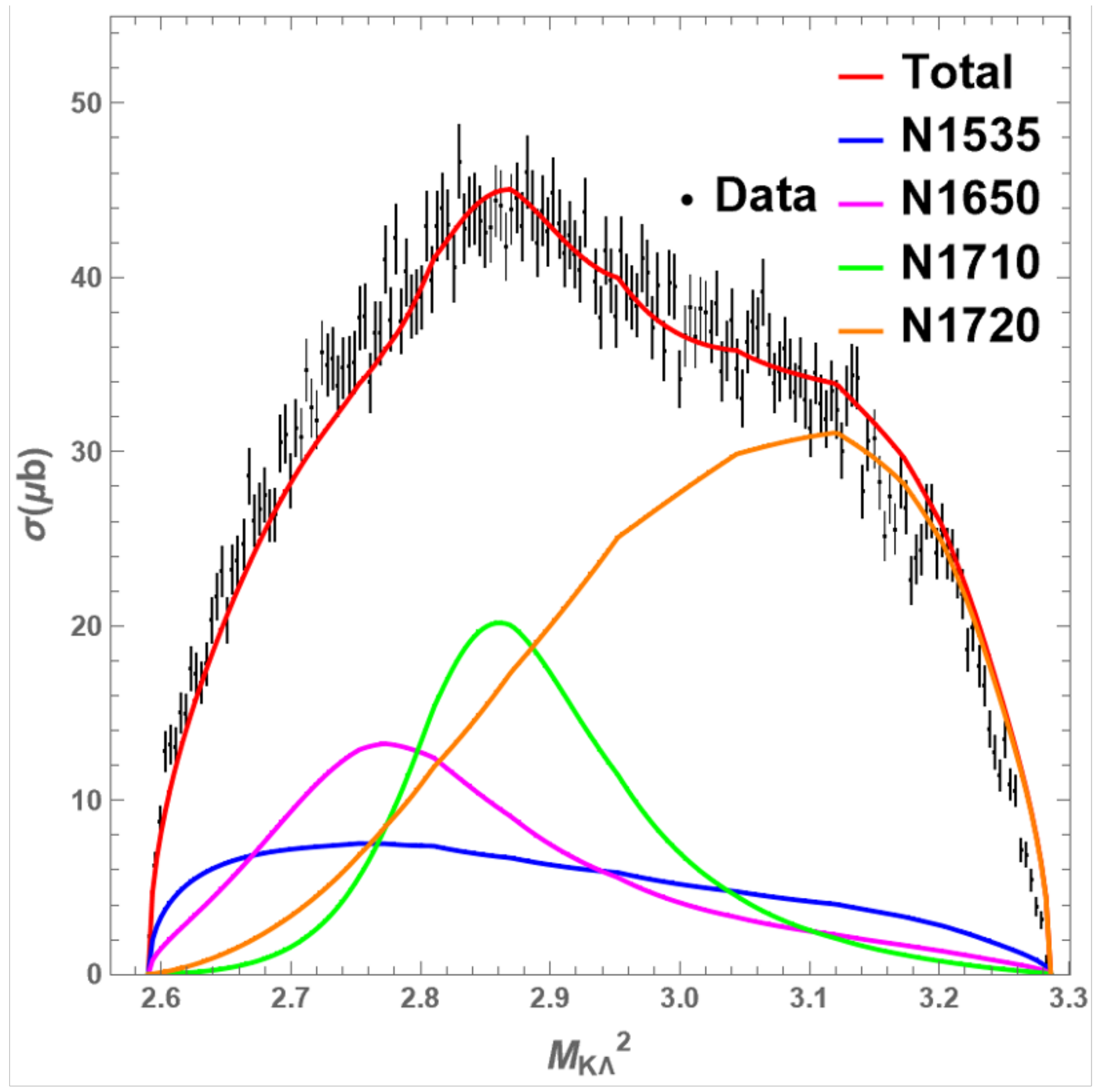


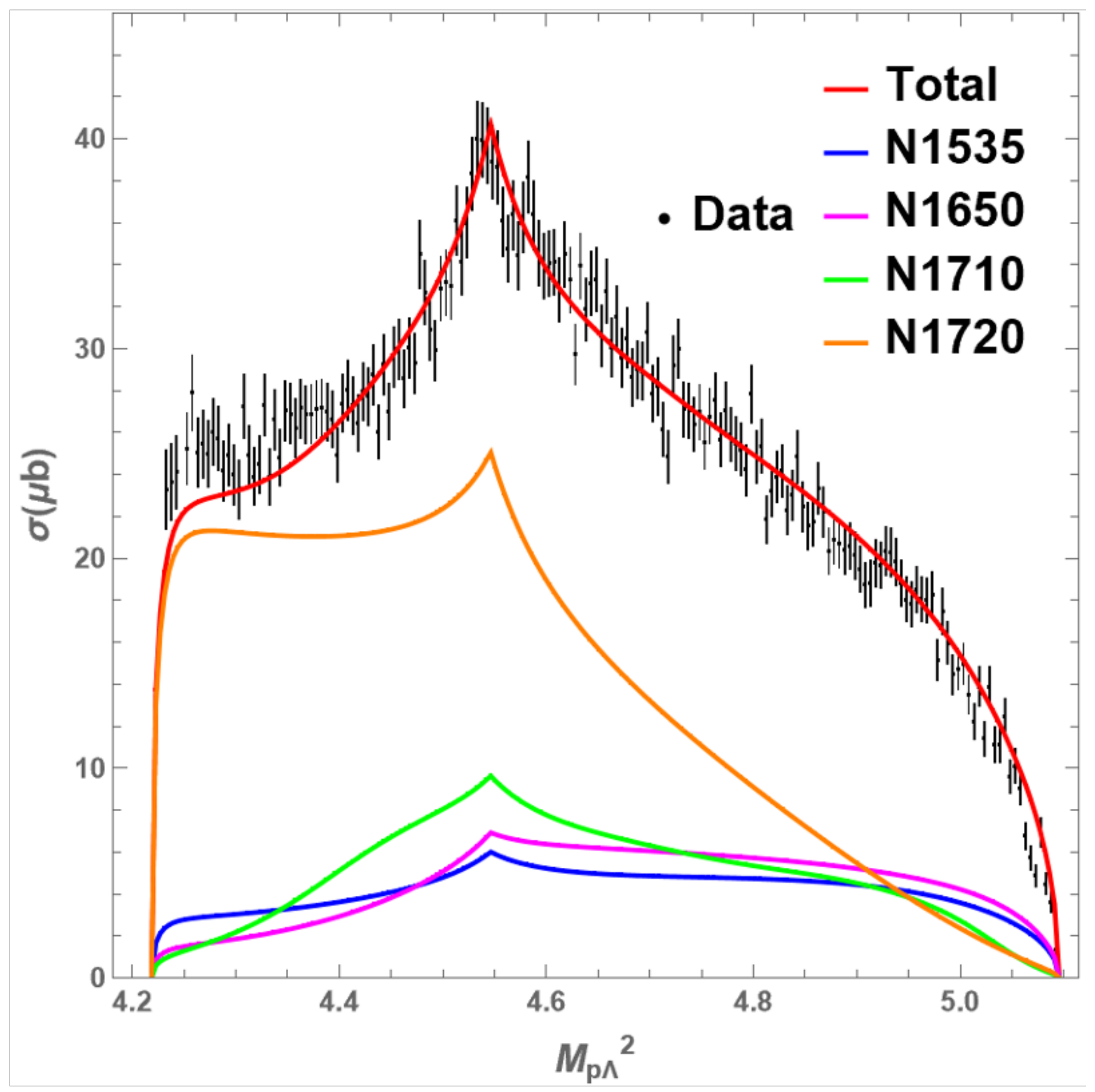
详见张哲的报告

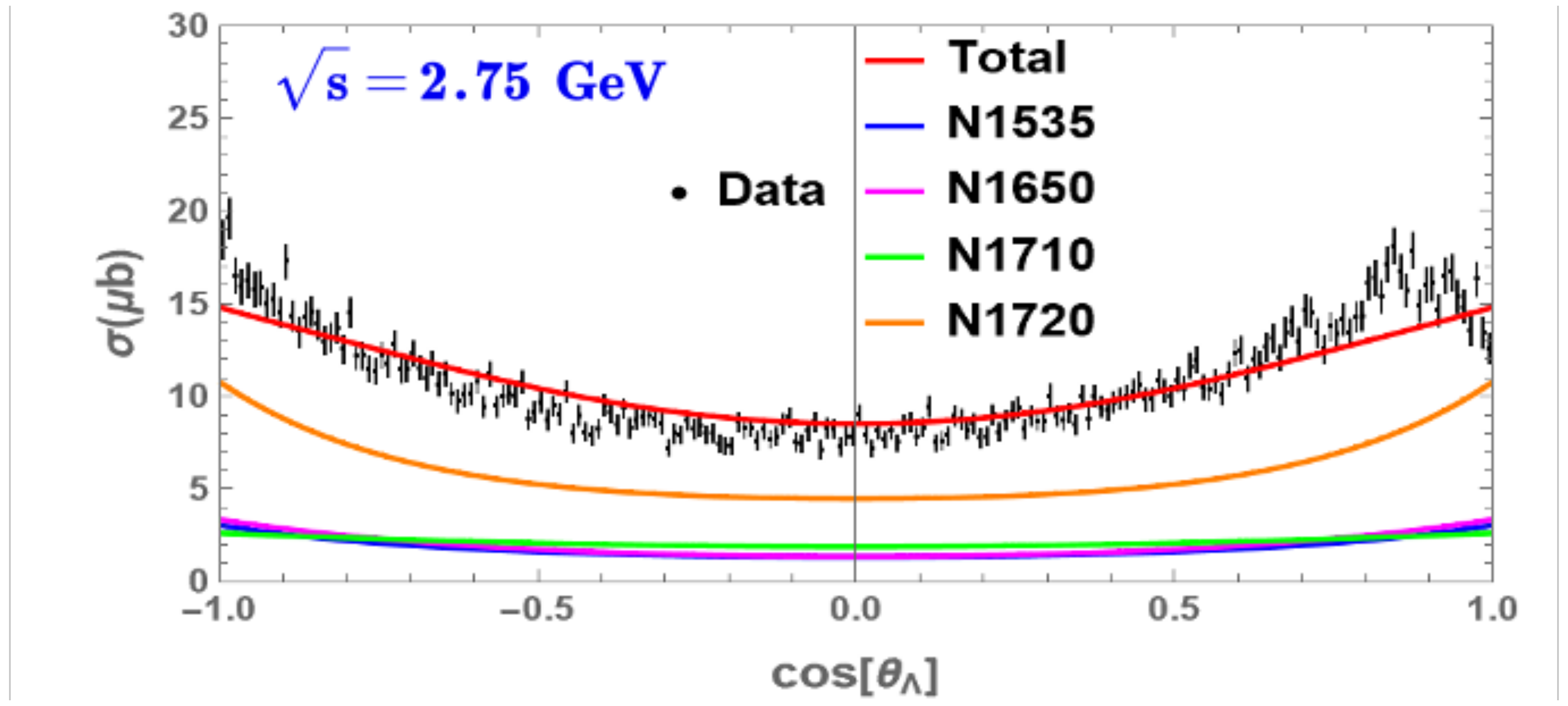
Zhe Zhang, Xu Cao, Bo-Chao Liu, Tianbo Liu, Jia-Jun Wu, Yuxiang Zhao, Bing-Song Zou, in preparation

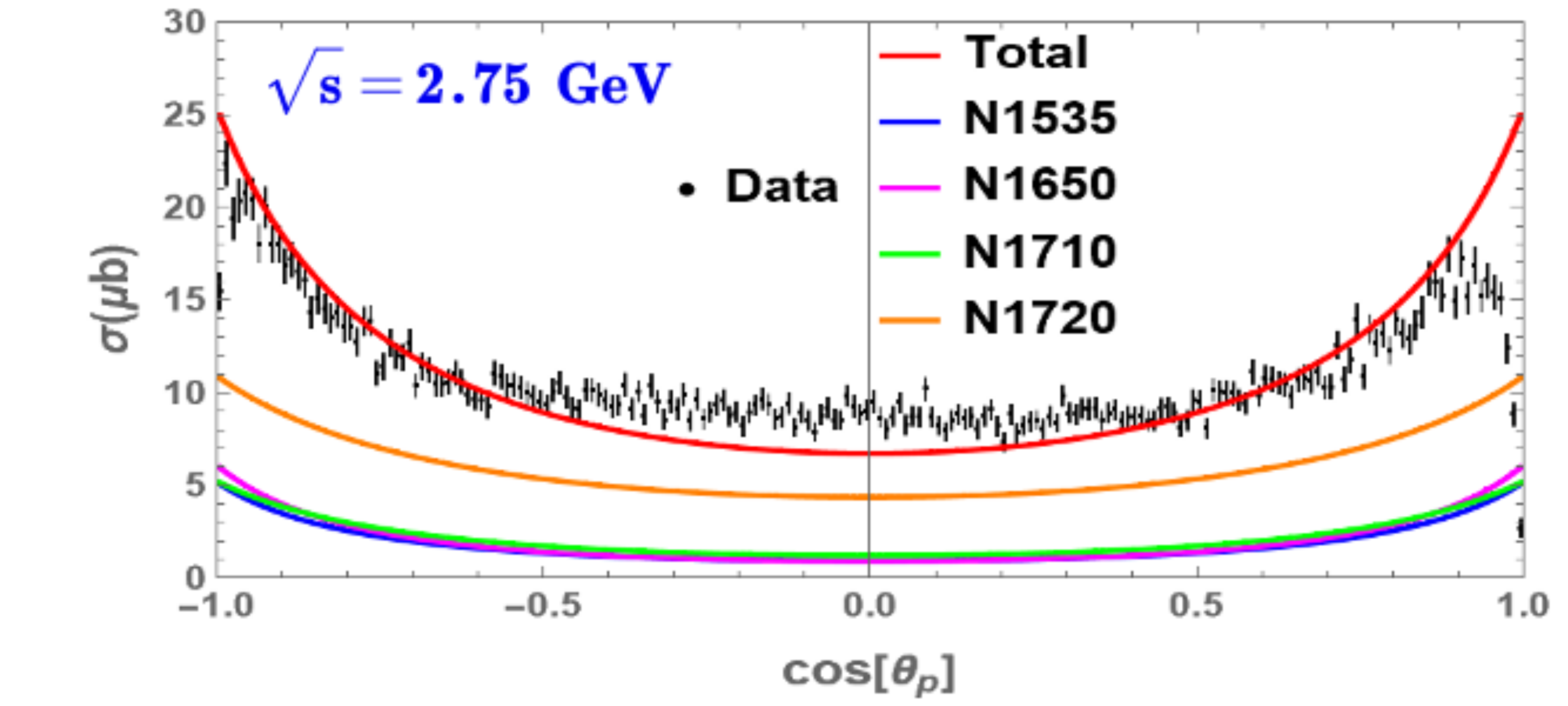
$pp \to pK^+\Lambda$过程的介子交换模型计算

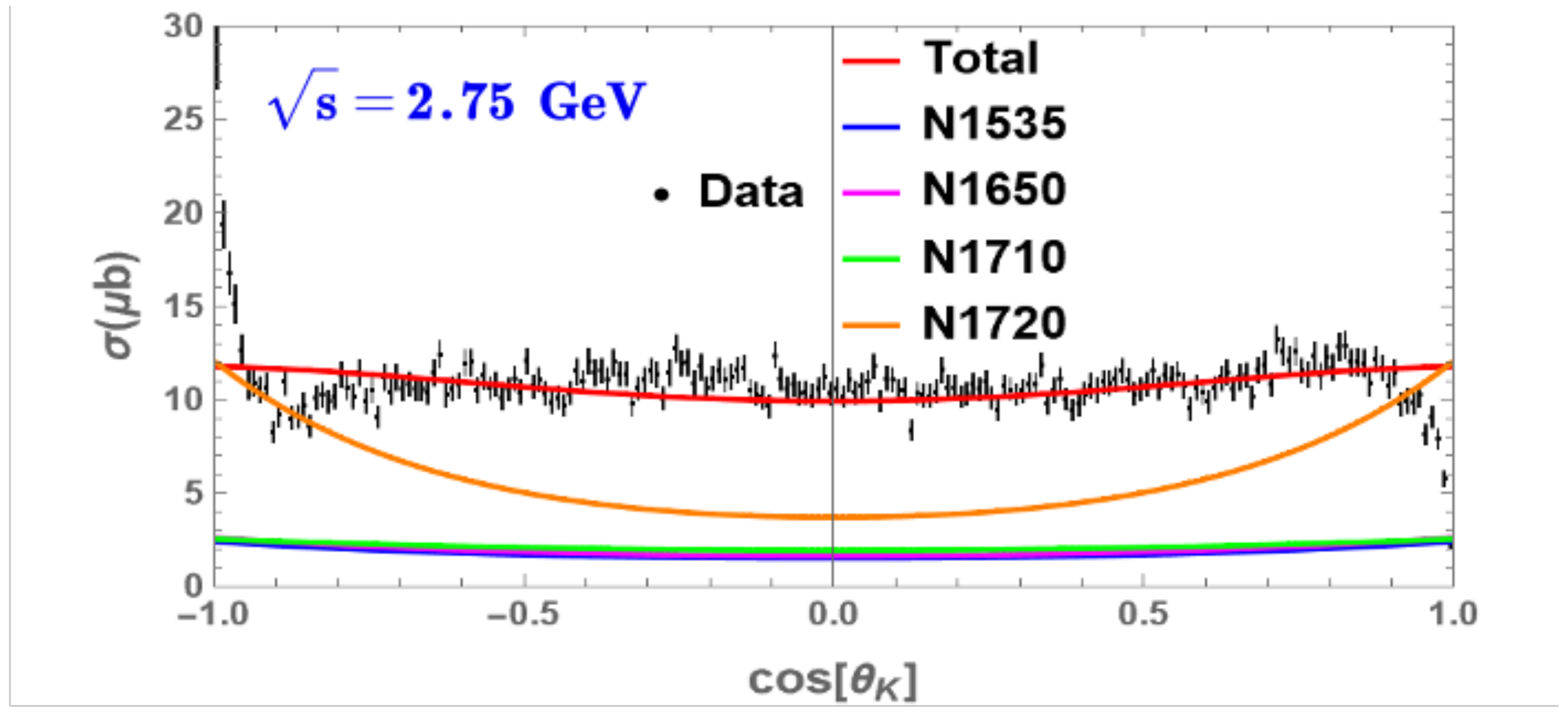
微分截面









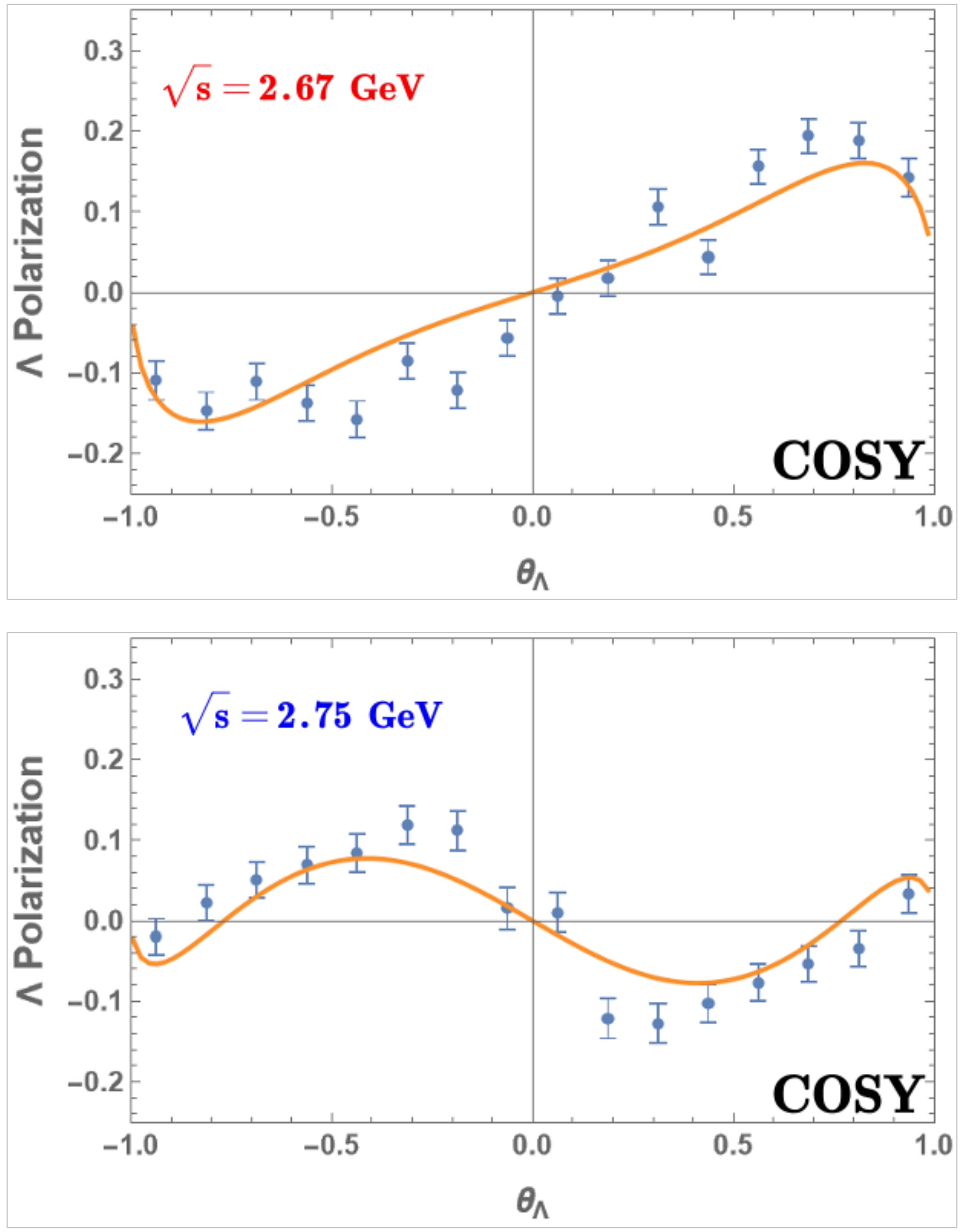


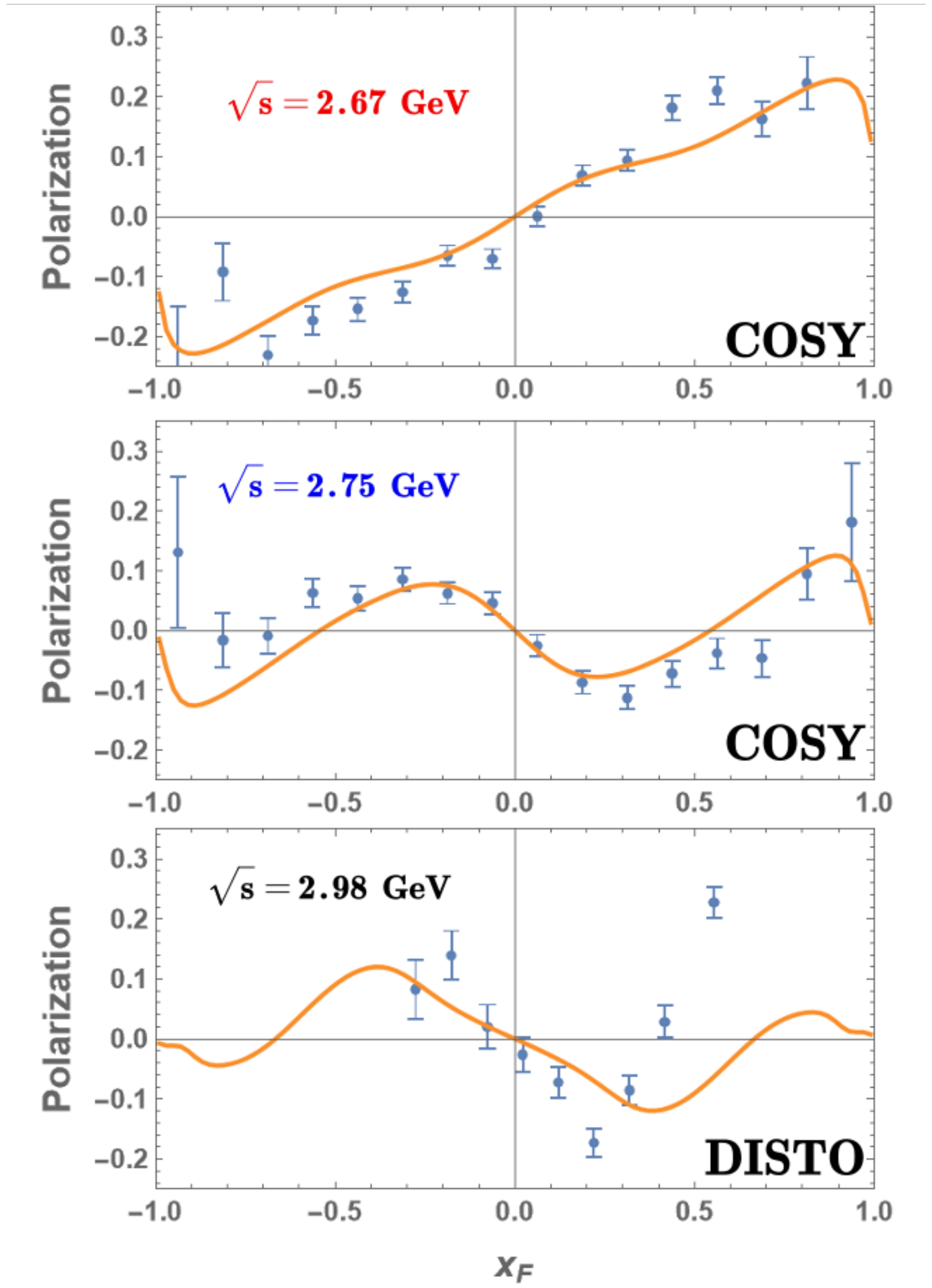
Zhe Zhang, Xu Cao, Bo-Chao Liu, Tianbo Liu, Jia-Jun Wu, Yuxiang Zhao, Bing-Song Zou, in preparation

$pp \to pK^+\Lambda$过程的介子交换模型计算

Λ超子极化

源自不同共振态
振幅相对相位

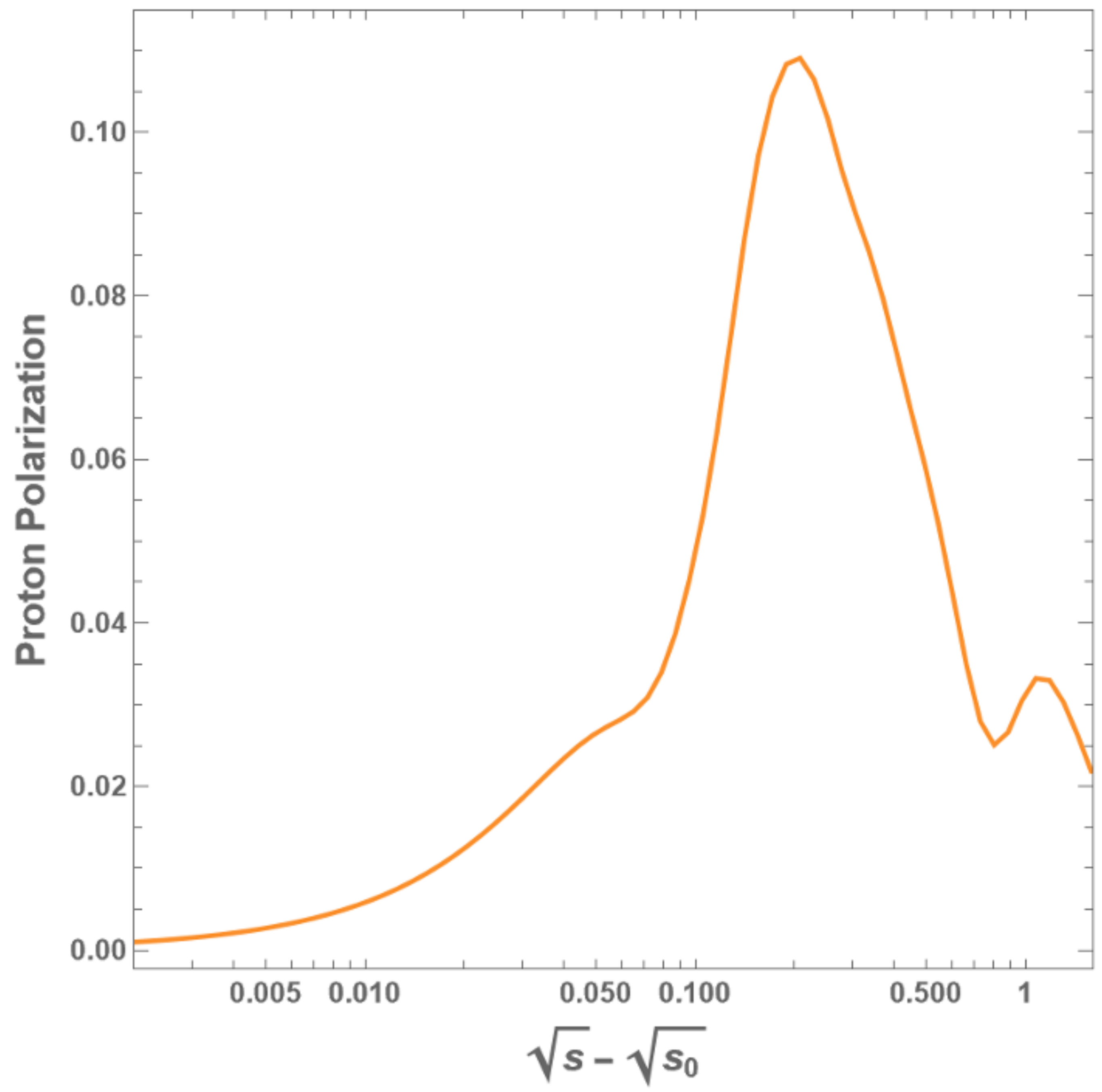


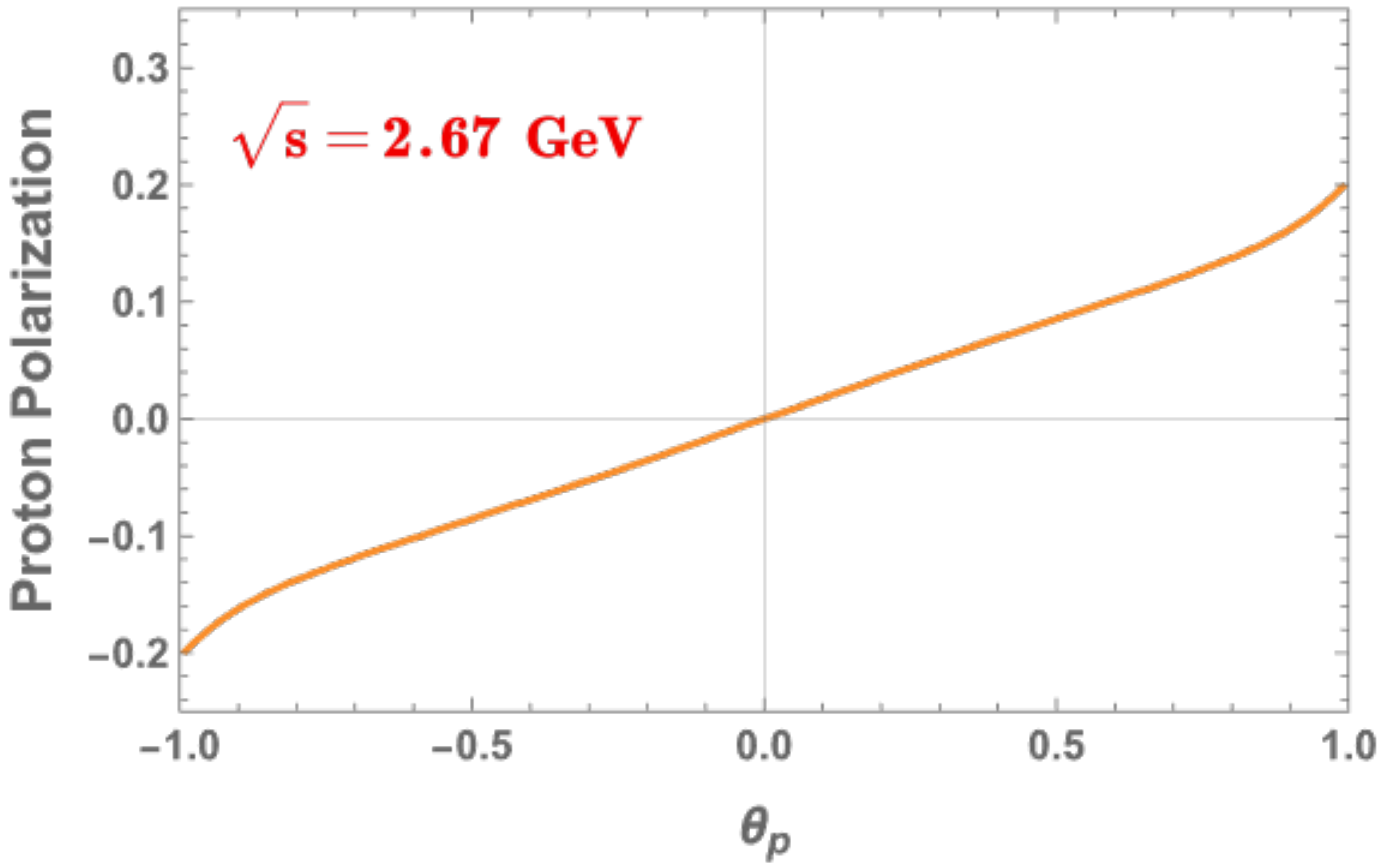


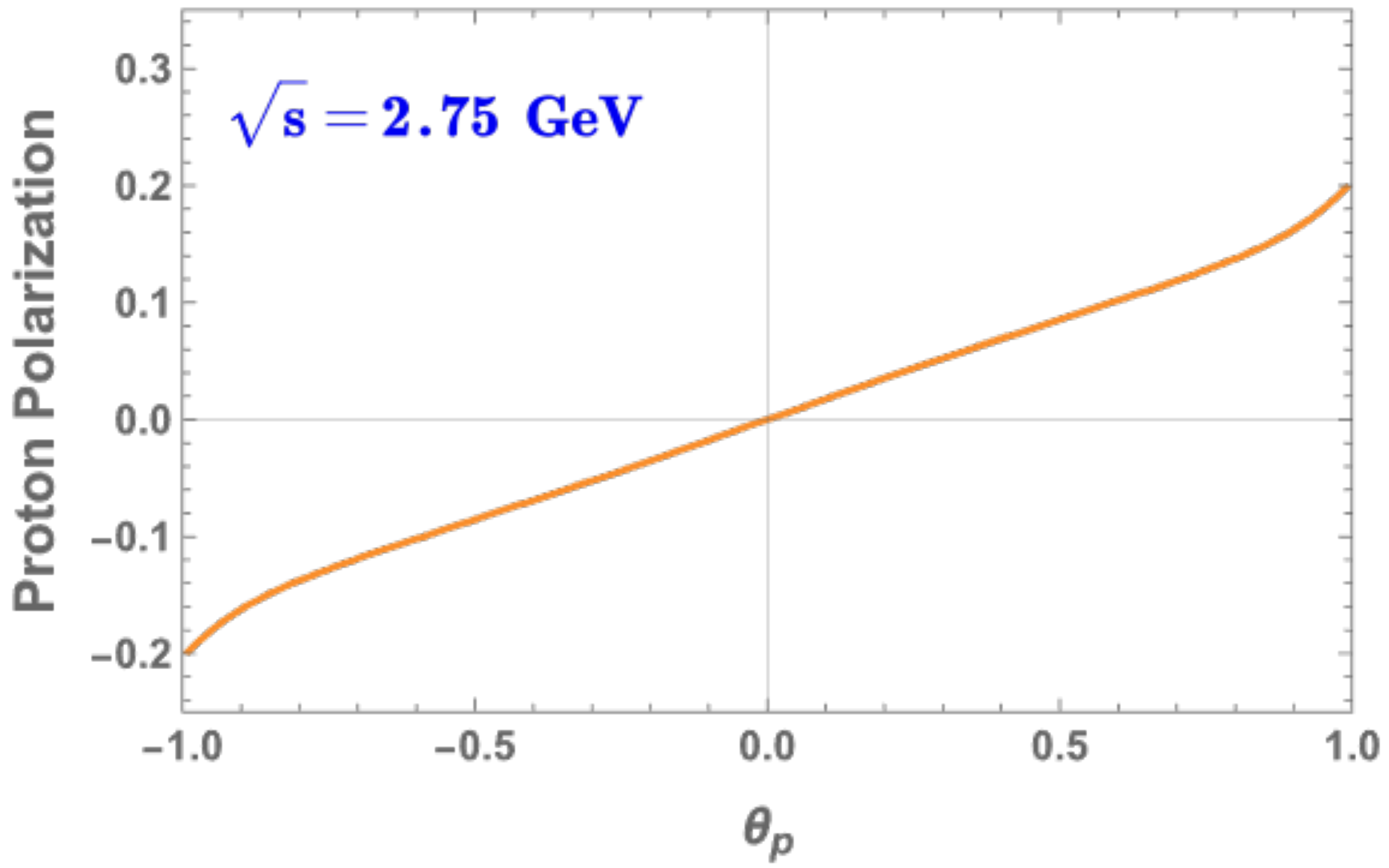
Zhe Zhang, Xu Cao, Bo-Chao Liu, Tianbo Liu, Jia-Jun Wu, Yuxiang Zhao, Bing-Song Zou, in preparation

$pp \to pK^+\Lambda$过程的介子交换模型计算

质子极化





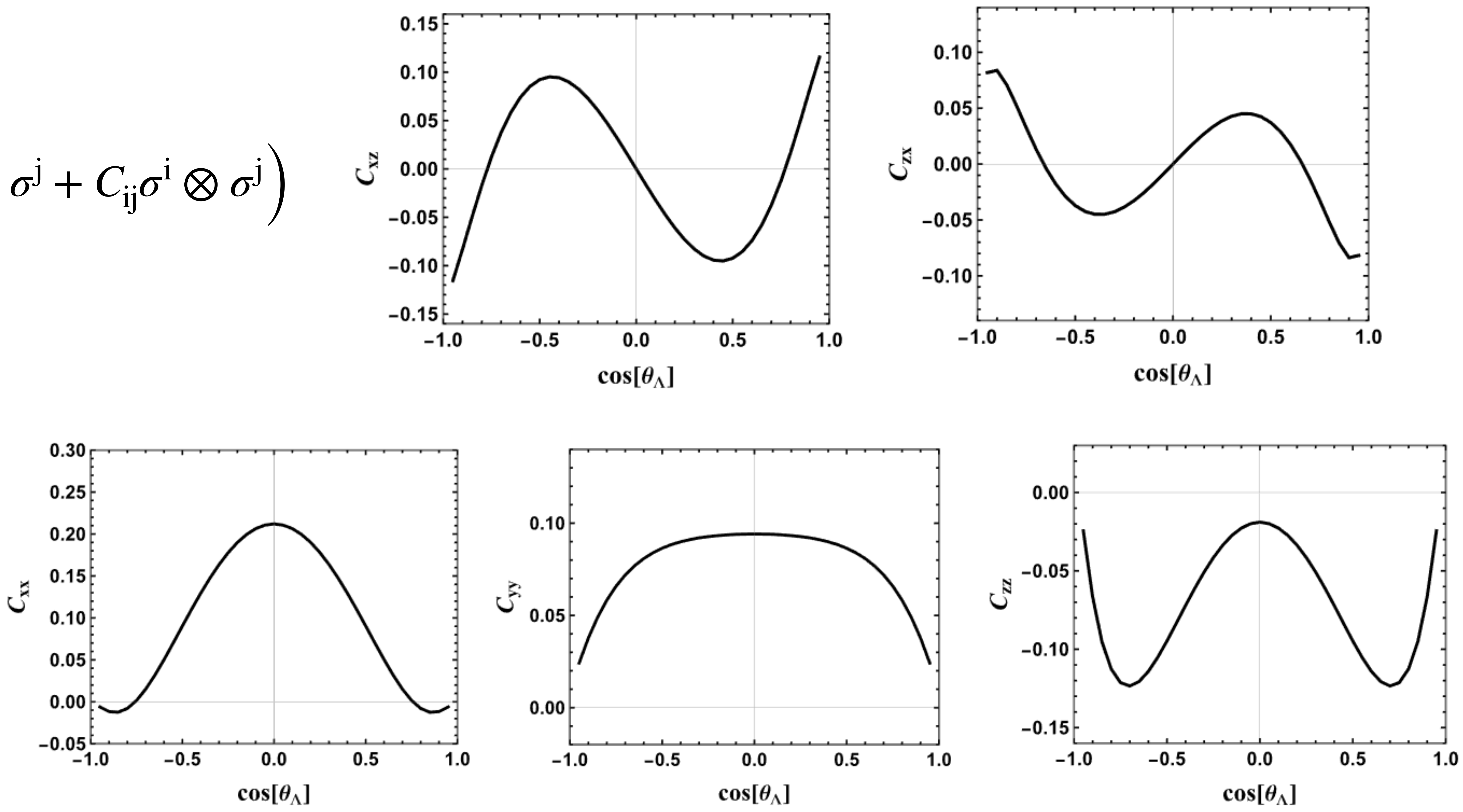


Zhe Zhang, Xu Cao, Bo-Chao Liu, Tianbo Liu, Jia-Jun Wu, Yuxiang Zhao, Bing-Song Zou, in preparation

$pp \to pK^+\Lambda$过程的介子交换模型计算

超子-质子极化关联

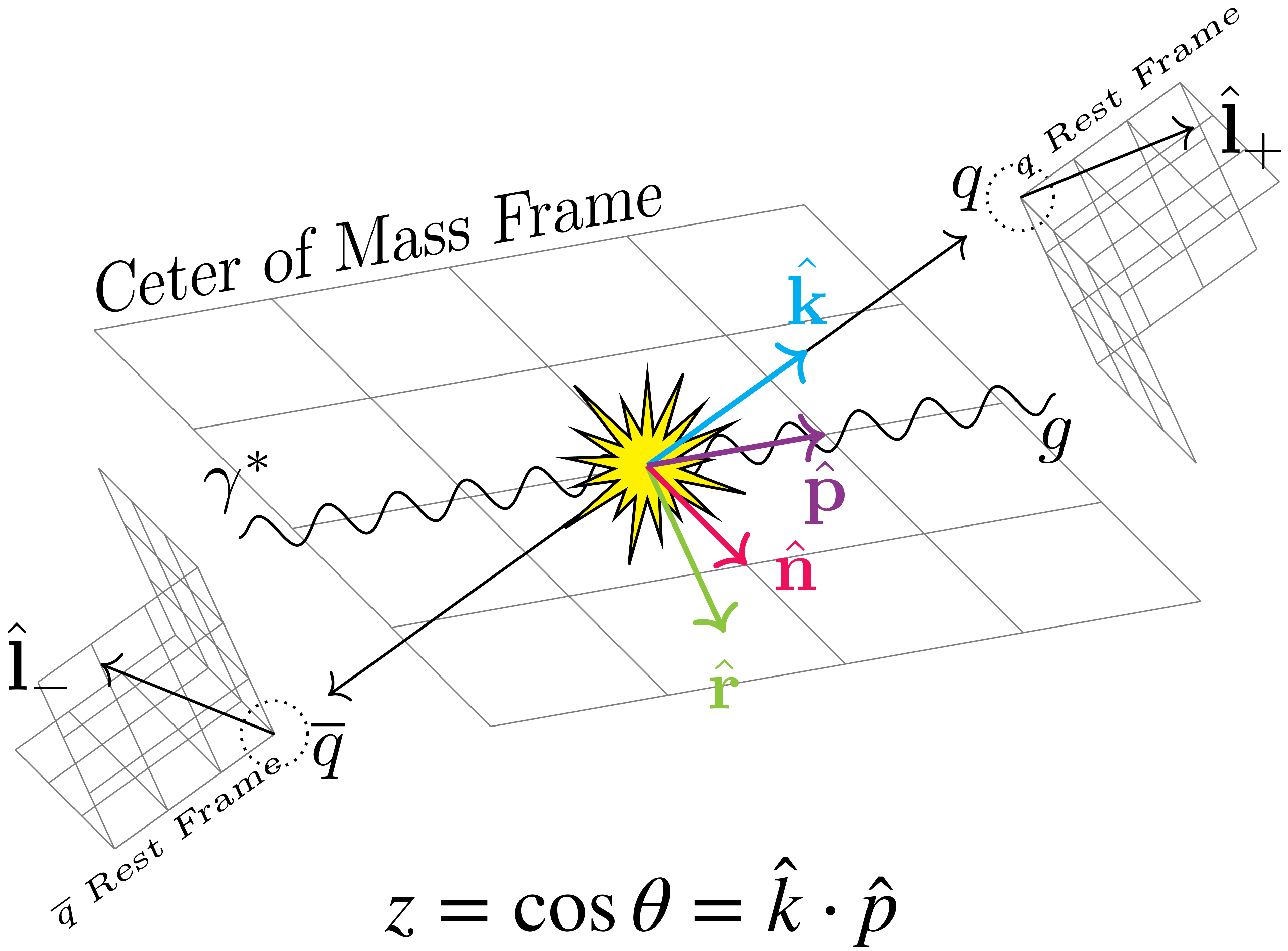
$$\rho = \frac{1}{4}\left(1_4 + B_{\mathrm{i}}^{p}\sigma^{\mathrm{i}} \otimes 1_2 + B_{\mathrm{j}}^{\Lambda} 1_2 \otimes \sigma^{\mathrm{j}} + C_{\mathrm{ij}}\sigma^{\mathrm{i}} \otimes \sigma^{\mathrm{j}}\right)$$



Zhe Zhang, Xu Cao, Bo-Chao Liu, Tianbo Liu, Jia-Jun Wu, Yuxiang Zhao, Bing-Song Zou, in preparation

高能产生正反夸克对的量子纠缠效应

虚光子-胶子熔合的正反夸克对产生过程



$$z = \cos\theta = \hat{k}\cdot\hat{p}$$

详见肖博文的报告

$$\rho = \frac{1}{4}\left(\mathbf{1}_4 + B_i^+\sigma^i \otimes \mathbf{1}_2 + B_j^- \mathbf{1}_2 \otimes \sigma^j + C_{ij}\sigma^i \otimes \sigma^j\right)$$

$$\Delta_1 = -1 + C_{nn} + \sqrt{\left(C_{rr} - C_{kk}\right)^2 + \left(C_{rk} + C_{kr}\right)^2}$$

$$\Delta_2 = -1 - C_{nn} + \sqrt{\left(C_{rr} + C_{kk}\right)^2 + \left(C_{rk} - C_{kr}\right)^2}$$

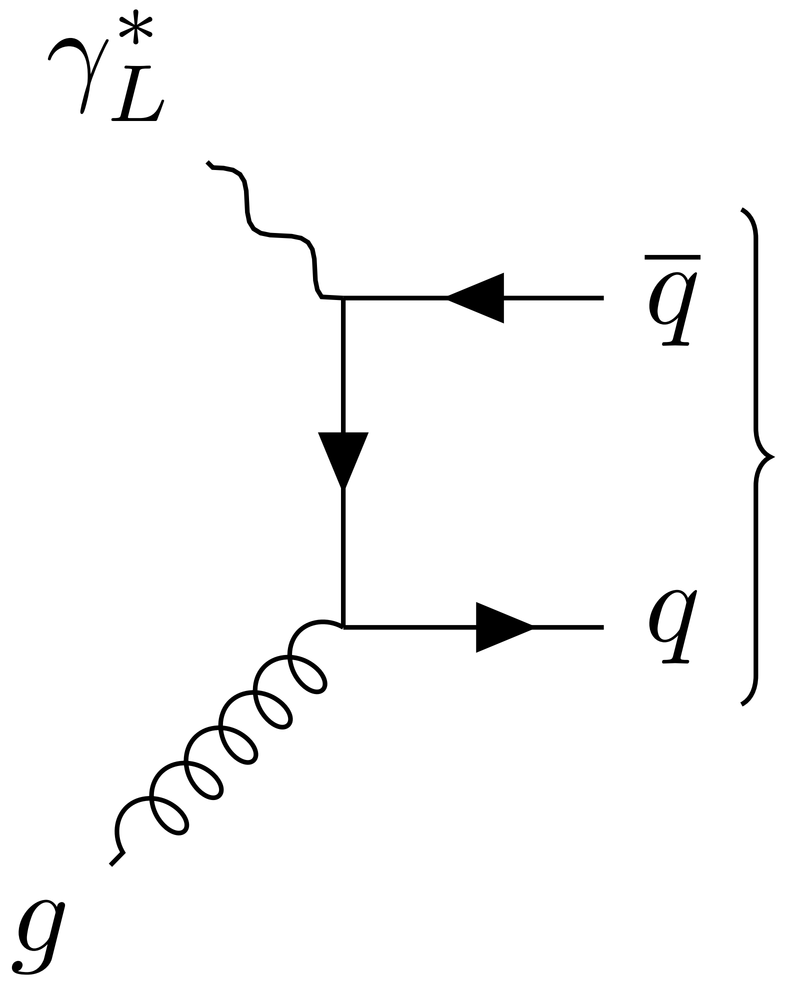
量子纠缠判据：$\Delta_1 > 0$ 或 $\Delta_2 > 0$

$$\mathscr{C}[\rho] \equiv \max\{\Delta_1/2,\ \Delta_2/2,\ 0\} \in [0,1]$$

Wei Qi, Zijing Guo, Bo-Wen Xiao, PRD 113, 054048 (2026).

高能产生正反夸克对的量子纠缠效应

纵向极化虚光子反应道



$$C = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -\chi_1 & -\chi_2 \\ 0 & -\chi_2 & \chi_1 \end{pmatrix}$$

$$\chi_1 = \frac{1 - 2z^2 + z^2\beta^2}{1 - z^2\beta^2}$$

$$\chi_2 = \frac{2z\sqrt{\left(1 - z^2\right)\left(1 - \beta^2\right)}}{1 - z^2\beta^2}$$

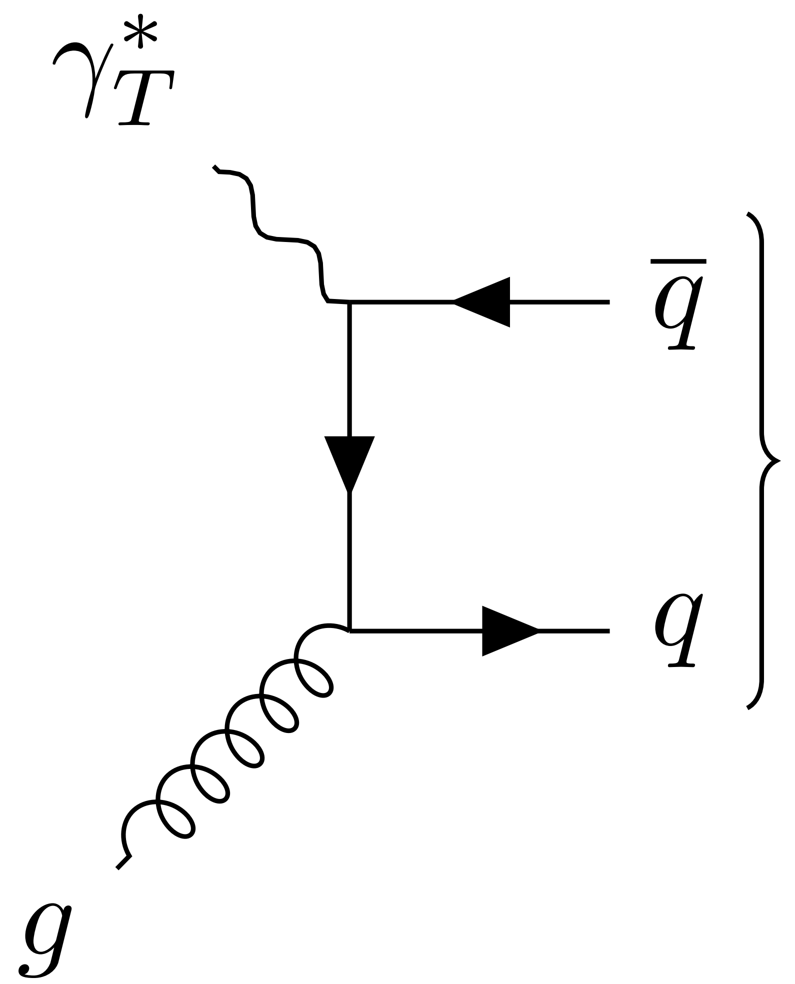
$$\beta = \sqrt{1 - 4m^2/\hat{s}}$$

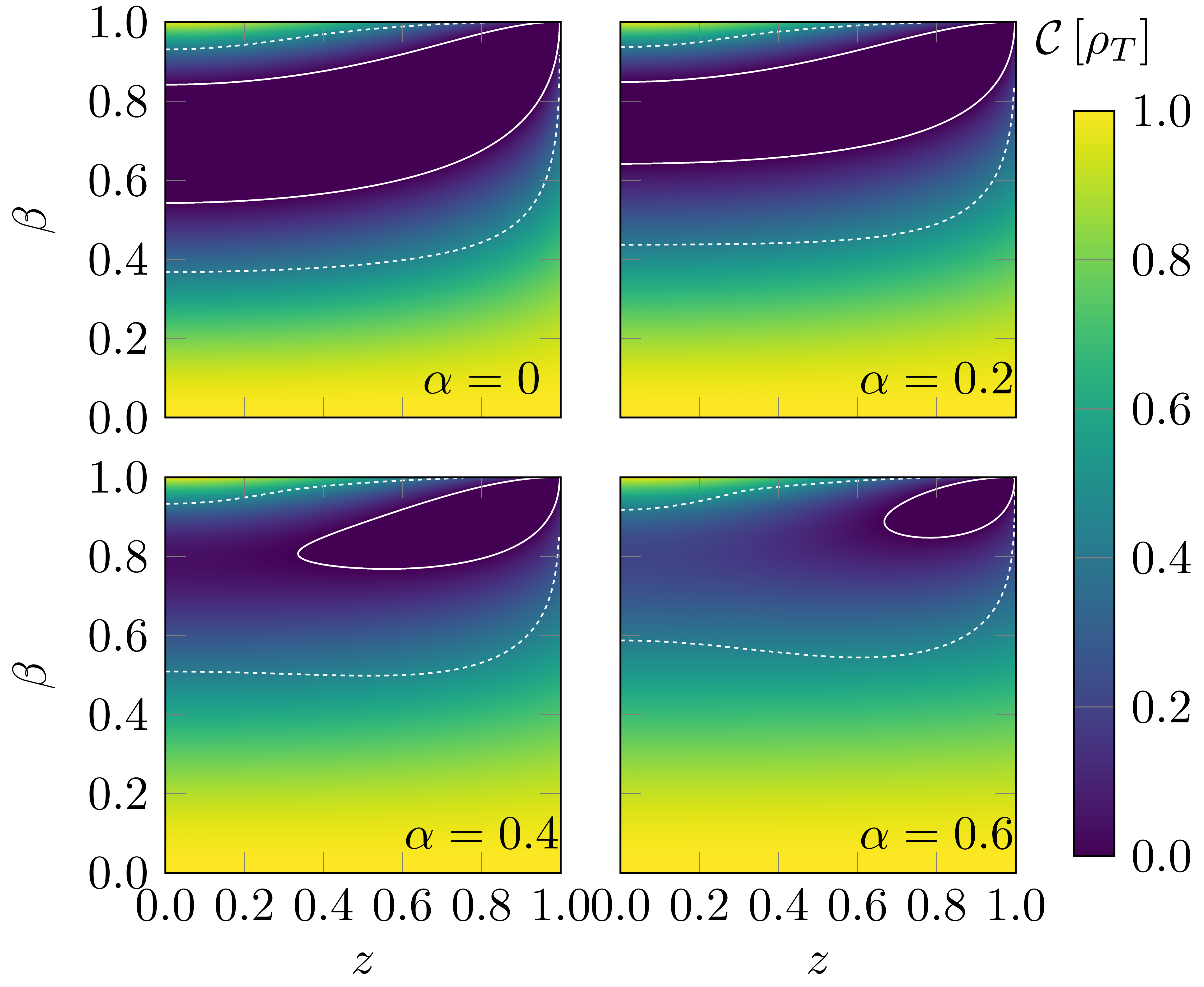
此时 $\mathscr{C}[\rho] = 1$，为最大纠缠

Wei Qi, Zijing Guo, Bo-Wen Xiao, PRD 113, 054048 (2026).

高能产生正反夸克对的量子纠缠效应

横向极化虚光子反应道





$$\alpha = Q^2/\hat{s}$$

$$\beta = \sqrt{1 - 4m^2/\hat{s}}$$

Wei Qi, Zijing Guo, Bo-Wen Xiao, PRD 113, 054048 (2026).

总结

- 揭示DIS过程Λ超子产生的靶碎裂贡献与其对自旋转移信号的压低效应，解决了实验与理论的长期冲突，并被JLab-CLAS实验进一步验证。
- 基于介子交换模型计算$pp \to pK\Lambda$遍举过程，考虑$N(1535)$, $N(1650)$, $N(1710)$, $N(1720)$共振态贡献及各反应道振幅相对相位，成功描述COSY等实验微分截面与Λ极化数据，并预言质子极化和超子-质子极化关联。将作为H-NS相关物理模拟的理论输入。
- 探索高能散射中夸克-反夸克对产生的量子纠缠效应，可能成为探测核物质环境和超子产生的新探针。